

DOT/FAA/AR-02/82

Office of Aviation Research
Washington, D.C. 20591

Development of a Procedure for Indoor Testing of Type IV Fluids to Replicate Natural Snow

August 2002

Final Report

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1. Report No. DOT/FAA/AR-02/82		2. Government Accession No.		3. Recipient's Catalogue No.	
4. Title and Subtitle DEVELOPMENT OF A PROCEDURE FOR INDOOR TESTING OF TYPE IV FLUIDS TO REPLICATE NATURAL SNOW				5. Report Date August 2002	
				6. Performing Organization Code	
7. Author(s) Arlene Beisswenger, Kathy Bouchard, and Jean-Louis Laforte				8. Performing Organization Report No.	
9. Performing Organization Name and Address Anti-icing Materials International Laboratory Université du Québec à Chicoutimi 555, boulevard de l'Université Chicoutimi, Québec G7H 2B1				10. Work Unit N. (TRAIS)	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Atlantic City International Airport New Jersey, U.S.A. 08405				13. Type of publication and Period Covered Final report	
				14. Sponsoring Agency Code AFS-220	
15. Supplementary Notes This report was produced for the Federal Aviation Administration on behalf of civil aviation. The FAA William J. Hughes Technical Center COTR was Paul Boris.					
16. Abstract Outdoor snow tests were performed on flat plates to evaluate the anti-icing performance of SAE Type IV aircraft anti-icing fluids. These tests were conducted at three sites using the same test protocol. The data from the three sites were analyzed and compared on anti-icing endurance time versus snow intensity graphs where the relationship was roughly equivalent to a negative power law. A regression analysis was made using this negative power law and confidence intervals from 50% to 95% were defined. Indoor tests were then carried out replicating the temperature and snow intensity conditions encountered outdoors. The indoor tests were performed using artificially made snow which was then evenly distributed onto a test plate by means of the AMIL snow distribution machine. The indoor results for two fluids, Kilfrost ABC-S and SPCA AD-480, fell between the lower 95% confidence interval and the mean regression line of the outdoor data, while the results for Dow Ultra+ fell between the mean regression line and the upper 95% confidence interval. Four deviations between indoor and outdoor tests were investigated in order to resolve the differences in results. First, natural snow was placed in the snow distribution machine to see if there was a difference in absorption capability with respect to artificially made snow—no significant difference was seen. Second, two different snow cluster sizes were examined—no significant difference was seen in fluid endurance time. Third, the failure call of snow versus slush was examined, and 30% snow cover was found to more closely resemble the results of the outdoor tests. The fourth factor investigated was the effect of wind. Outside, the wind provides better convection around the test plate allowing the plate, fluid, and air temperatures to equilibrate faster, while inside these temperatures can be a few degrees different because of the lack of wind. By improving air circulation in the indoor tests, or by directly controlling the plate temperature, the results more closely resembled the results obtained outdoors.					
17. Key Words Snow, Artificial snow, Anti-icing endurance time, Precipitation simulation, HOT table, Aircraft anti-icing fluids, Type IV fluids, Snow generation				18. Distribution Statement This document is available to the public through the National Technical Information Service (NTIS) Springfield, Virginia 22161.	
19. Security Classification (of this report) Unclassified		20. Security Classification (of this page) Unclassified		21. No. of Pages 56	
22. Price					

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EXECUTIVE SUMMARY

Outdoor snow tests on flat plates were performed to evaluate the anti-icing performance of three SAE Type IV aircraft anti-icing fluids and their dilutions—Kilfrost ABC-S, SPCA AD-480, and Dow Ultra+. These tests were conducted at the following three sites using the same test protocol:

- Chicoutimi, Quebec, conducted by AMIL
- Dorval, Quebec, conducted by APS
- Boulder, Colorado, conducted by NCAR

The data from the three sites were analyzed and compared on anti-icing endurance time versus snow intensity graphs where the relationship was roughly equivalent to a negative power law. A regression analysis was made using this negative power law and confidence intervals from 50% to 95% were drawn.

Indoor tests were carried out replicating the temperature and snow intensity conditions encountered outdoors. The indoor tests were performed using artificially made snow, which was evenly distributed onto a test plate by means of the AMIL snow distribution machine.

Most indoor data collected fell within the upper and lower 95% confidence intervals determined from the outdoor data. The indoor results for two fluids, Kilfrost ABC-S and SPCA AD-480 fell between the lower 95% confidence interval and the mean regression line of the outdoor data, while the results for Dow Ultra+ fell between the mean regression line and the upper 95% confidence interval.

Four deviations between indoor and outdoor tests were investigated in order to resolve the differences in the results.

The first factor investigated was the ability of the fluids to absorb artificially generated snow as opposed to natural snow. This natural snow was placed in the AMIL snow distribution machine to see if there was a difference in absorption capability. No significant difference in fluid endurance time was seen.

The second factor investigated was the size of the snow clusters and the ability of the fluid to absorb them. The AMIL snow distribution machine deposits the artificially made snow in the form of discreet clusters onto the test plate. Two different snow cluster sizes were tested to see if there was any difference in endurance time. No significant difference was seen when smaller snow clusters were used. However, since the smaller snow cluster lead to better snow distribution and more representative failure modes, the smaller size was adapted in the laboratory.

The third factor investigated was the failure call of snow versus slush and 30% snow cover was found to more closely resemble the results of the outdoor tests.

The fourth factor investigated was the effect of wind. Outside, the wind provides better convection around the test plate allowing the plate, fluid, and air temperatures to equilibrate faster; while inside, these temperatures can be a few degrees different because of the lack of wind. Inside, this effect was investigated with three different setups. The first setup consisted of adding wind under the test plate by means of a small fan. This led to reduced differences between air and the plate temperatures and endurance times that more closely resembled those obtained outdoors. The second setup consisted of placing a fan above the test plate, so the wind was directly impacting the fluid. This led to variable results, more favorable for Kilfrost ABC-S but less for SPCA AD-480 and Dow Ultra+. The third setup examined consisted of a recirculating heat transfer fluid under the test plate which allowed to match the plate and air temperatures. Only preliminary tests were run with this setup, but it showed much promise as the outdoor and indoor test results were within the lower 60% to the upper 50% confidence intervals for the three fluids. More tests are needed with this setup. Its advantage is that this was the situation observed outside, where the plate and air temperatures were the same, and it is best suited to perform controlled reproducible test conditions for indoor standard testing.

1. INTRODUCTION.

The Federal Aviation Administration's (FAA) William J. Hughes Technical Center continues to support research and related efforts directed toward the improvement of aircraft deicing methods and practices. One such effort is the standardization of holdover time (HOT) test procedures for deicing/anti-icing fluids. New products are constantly being introduced and each must be certified per published SAE fluid specifications. Among these requirements is the testing for HOT under various freezing/frozen precipitation conditions. These tests are performed in a laboratory environment, with one notable exception, namely, snow. The simulation of snow in the laboratory to yield results equivalent to that of natural snow has been an elusive goal and is one of the reasons why pending standardized HOT procedures have not yet been approved by the SAE G-12 Aircraft Ground Deicing Committee.

Current protocol dictates that endurance time testing of fluids for snow be accomplished outdoors during the winter months. The final acceptance of a new fluid must await the completion of winter testing. The endorsement by the international aviation community of a suitable laboratory method for testing under snowfall conditions would make HOT testing an endeavor independent of weather conditions and thus, eliminate outdoor winter testing. This would be a major step forward toward the adoption of standardized HOT procedures.

In order to remedy this the William J. Hughes Technical Center contracted AMIL at the Université du Québec à Chicoutimi to run outdoor tests and develop an indoor simulated snow test [1]. The simulated snow machine proved valid for SAE Type I and II deicing/anti-icing fluids by producing similar endurance time data as were obtained outdoors. Through a similar contract, The National Center for Atmospheric Research (NCAR) also developed a snow machine capable of producing indoors endurance time data similar to that produced outdoors for Type I and II fluids [2]. However, when these machines are used on Type IV anti-icing fluids, the times are consistently shorter. Furthermore, the endurance time data generated by both machines generated different times under different conditions. This study aims to resolve those differences, so both machines obtain the same results as outdoors under natural snow conditions.

1.1 OBJECTIVE.

The objective of this study is to conduct outdoor testing of Type IV anti-icing fluids under natural snowfall and compare the results to tests duplicated in a laboratory environment using artificially generated snow and AMIL's snow distribution machine. This will involve the following:

- a. Perform outdoor endurance time testing under a variety of snowfall intensities and outside air temperatures (OAT) with SAE Type IV aircraft anti-icing fluids
- b. Select a suitable number of representative tests from objective (a.) and duplicate them in a laboratory environment
- c. Compare indoor and outdoor test results

1.2 SCOPE.

The scope of this study is limited to endurance time testing of Type IV aircraft anti-icing fluids under conditions of natural snowfall and snowfall generated under laboratory conditions. Laboratory investigations for this study include

- Ability of fluids to absorb artificial versus natural snow evaluated by running outdoor and indoor tests with natural and artificial snow
- Failure call (slush versus white snow; at is 30% of the plate) evaluated by visits to other test sites
- Fluid temperature and characteristics evaluated by running tests with different plate temperatures
- Procedure evaluated by replicating inside the procedure used for outdoor tests

2. OUTDOOR SNOW TESTS.

2.1 METHODOLOGY.

2.1.1 Outdoor Snow Test Procedure.

The procedure used for outdoor tests was agreed upon by the three participating laboratories conducting outdoor tests (AMIL, APS, and NCAR), as well as the FAA and Canada's Transportation Development Centre (TDC).

The procedure agreed upon consisted of pouring 1 liter of fluid onto 30- by 50-cm plates inclined at a 10° angle. The test plates were unpolished aluminum alloy 2024-T6. The test plates were cleaned with a squeegee in between test runs with the same fluid or a dilution thereof. When the fluid was changed, the plate was cleaned with ethanol. At AMIL, a set of two plates was designated for each fluid, or dilutions thereof, and therefore, the same plate was always used for the same fluid, thereby no ethanol was required and plates could be cleaned with a squeegee.

The fluids poured on the test plates were at, or close to, ambient temperature. This was achieved at AMIL by leaving the fluids outdoors in most cases, except for the 50/50 dilutions, which risked freezing in temperatures below -5°C. The temperature of the fluid was recorded prior to pouring the fluid. The fluids were poured as delivered on the test plate with no further shearing. There was no wait time following the pouring of the fluid before being exposed to the snow.

During the course of testing, the following quantities were measured: air and plate temperature in real-time throughout the test, as well as wind speed and direction, and snowfall rate.

Failure was considered when 30% of the plate was cover with white snow. At AMIL, the 30% was estimated using a line drawn on the plate at 15 cm from its top.

A sample of the fluid was collected before the tests and half way down the plate at failure to measure refractive index. A picture was taken at failure and 5 minutes following fluid failure.

The type of snow crystals and their size was recorded based on the International Commission of Snow classification [3] and a picture was taken of the snow crystals on a black velvet-covered board.

2.1.2 Test Fluids.

Three fluids were used for the tests (see table 1). All fluids were SAE Type IV fluids. Two of which were propylene glycol-based (Kilfrost ABC-S and SPCA AD-480) and one was ethylene glycol-based (Dow Ultra+).

TABLE 1. FLUID IDENTIFICATION

Company Name	Fluid	Color	AMIL Label	Reception Date
Dow chemical company	Ultra+ Lot# 448378 Neat	Green	C971	2001-01-03
Kilfrost limited	ABC-S Lot# S/93/12/00 Neat	Green	C975	2001-01-10
Kilfrost limited	ABC-S Lot# S/93/12/00 75/25	Green	C976	2001-01-10
Kilfrost limited	ABC-S Lot# S/93/12/00 50/50	Green	C977	2001-01-10
SPCA	AD-480 Lot# M052 Neat	Green	E007	2001-01-29
SPCA	AD-480 Lot# M052 75/25	Green	E007	2001-01-29
SPCA	AD-480 Lot# M052 50/50	Green	E007	2001-01-29

Dilutions of 75/25 and 50/50 (with water) of the fluids were also tested in the case of the propylene glycol-based fluids, although fewer outdoor tests of the dilutions were carried out as compared to the neat fluids. The dilutions were prepared by the manufacturer. In the case of Ultra+, the dilutions were not tested, since for this fluid, the dilutions do not meet AMS 1428 requirements.

Type IV fluids are characterized by their anti-icing performance evaluated in the standard Water Spray Endurance Test (WSET), according to Annex A of AMS1428C [4]. This test consists of

exposing a 10- by 30-cm plate to a fine water spray at -5°C , with the plate temperature set at -5°C . To qualify as a Type IV fluid, a candidate fluid must present a standard WSET time, known as the First Icing Event (FIE), of at least 80 minutes. The FIE corresponds to the time required for the first ice crystal to reach a line drawn at 25 mm from the top of a 300-mm-long plate. Table 2 shows the results of the WSETs of the candidate fluids. It shows that all fluids meet and exceed the minimum required time for a Type IV fluid.

TABLE 2. WSET TIMES FOR FLUIDS TESTED

Fluid	WSET (FIE)
Ultra+	126 min
ABC-S	113 min
AD-480	97 min

2.1.3 Outdoor Test Setup.

The outdoor testing was setup on the roof of the University du Québec à Chicoutimi's main building. It consisted of a support, shown in figure 1, which holds six test plates and two snow-catch pans. Each test plate was equipped with a real-time data temperature probe linked to a data acquisition program, which recorded the plate temperature throughout each test. All test plates were inclined at a 10° angle from the horizontal.



FIGURE 1. OUTDOOR TEST SETUP SUPPORT

Two snow-catch pans were set to catch the snow alternately. Each pan was first coated with a film of an anti-icing fluid and weighed. Then, each pan was exposed in rotation, for 5 minutes, before being covered with a lid. At that time, the covered pan was carried into a nearby shed and weighed again, before being brought back to the test plate support. When the 5 minutes of

exposure was over, the lid was removed from the covered pan and another lid was placed on the exposed pan.

The layout of the test plates and snow-catch pans is show in figure 2. As mentioned in section 2.1, the same plates were used for each fluid or dilution thereof, therefore, only a squeegee clean was necessary. The test plates were fixed to the test support by magnetic strips glued to the bottom of the test plates and the test stand.

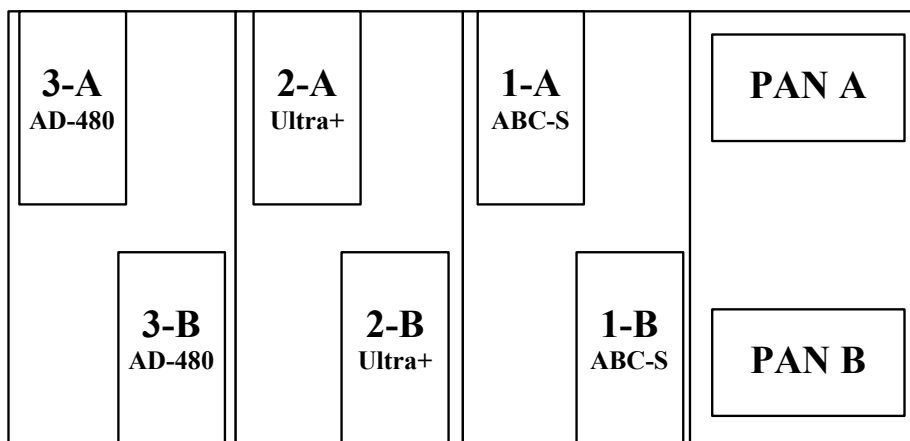


FIGURE 2. TEST PLATE AND SNOW CATCH PLATE LAYOUT ON OUTDOOR TEST PLATE SUPPORT

2.2 OUTDOOR SNOW TEST RESULTS—AMIL.

Twenty snow events took place in Chicoutimi between February 2000 and March 2001. Of the 20 events, 9 lasted long enough to measure anti-icing endurance times on fluids. An event of at least 2 hours was required in order to prepare, setup, and for the fluid to fail.



















For these nine snow events, 81 fluid failures were observed. Table 3 summarizes the conditions observed. The snow fall rate varied between 2 and 13 g/dm²/h, with an average of 6 /dm²/h. For events when the snow fall rate fell below 2 g/dm²/h, the tests were often stopped, since these lead to impossibly long anti-icing endurance times; over 4 hours. Unfortunately, no snow events with very high rates, above 15 g/dm²/h, occurred during the testing time. The air temperature for these tests ranged from +1° to -8°C, with an average of -5°C. No events were experienced at very low temperatures. The wind speed varied from 0 to 9 m/s with an average of 4 m/s. In rare events, the wind exceeded 9 m/s, but the data had to be rejected and the tests stopped, since testing in such conditions was nearly impossible because the fluid and snow would not stay on the plates, or in the snow-catch plates, rendering the rates immeasurable.

For the nine snow events, various crystal types were observed including stellar crystals, irregular crystals, spatial dendrites, plates, columns, capped columns, needles, and soft hail (see table 4). Their size varied from 0.2 to 5 mm.

TABLE 3. OUTDOOR SNOW EVENTS

Test No.	Average Snow Intensity (g/dm ² /h)	Average Air Temperature (°C)	Average Wind Speed (m/s)	Wind Direction	Fluid Failures
OS005	2.5	0	5.8	North West	1
OS006	7.5	-8	0.2	North East	5
OS009	6.1	-8	8.3	East then South	14
OS010	2.7	-6	2.4	North West	5
OS011	12.0	-8	5.6	East	10
OS012	7.5	-5	8.3	West	4
OS013	5.4	-5	0.6	East	11
OS014	6.6	-5	1.5	East	19
OS017	4.9	0.5	1.4	None	12
Average	6.1	-5.1	3.8		

TABLE 4. OUTDOOR TEST—SNOW CRYSTALS

Test No.	Crystal Type		Size
OS005		Stellar crystals	1 to 1.5 mm
		Spatial dendrites	
OS006		Plates	1 to 2 mm
		Stellar crystals	
		Spatial dendrites	
OS009		Spatial dendrites	0.2 mm
OS010		Spatial dendrites	0.4 to 1 mm
		Irregular crystals	
OS011		Columns	1 to 4 mm
OS012		Plates	0.5 to 2 mm
		Spatial dendrites	
OS013		Plates	0.25 to 5 mm
		Needles	
		Irregular crystals	
OS014		Spatial dendrites	0.5 to 1 mm
		Capped columns	
		Irregular crystals	
OS017		Soft hail	4 mm

2.2.1 Kilfrost ABC-S.

Twenty-nine tests were carried out on Kilfrost ABC-S-9 on the neat fluid, 18 on the 75/25 dilution, and 2 on the 50/50 dilution. The results are presented in table 5. A graph comparing snow fall rate and endurance time is presented in figure 3.

TABLE 5. OUTDOOR TEST RESULTS—KILFROST ABC-S

Test No.	Date	Fluid	Dilution	AMIL Code	AET (30% snow) (hr:min)	Average Snow Intensity (g/dm ² /h)	Average Wind Speed (km/h)	Average Air Temperature (°C)
OS006	2001-01-29	ABC-S	Neat	C975	02:22	7.0	0.5	-8
OS006	2001-01-29	ABC-S	Neat	C975	02:33	7.0	0.5	-8
OS009	2001-02-05	ABC-S	Neat	C975	04:02	5.3	22	-8
OS010	2001-02-06	ABC-S	Neat	C975	05:05	2.6	9	-6
OS011	2001-02-09	ABC-S	Neat	C975	01:56	10.8	19	-8
OS013	2001-02-14	ABC-S	Neat	C975	04:00	5.3	2	-6
OS014	2001-02-14	ABC-S	Neat	C975	02:50	7.8	3	-5
OS014	2001-02-14	ABC-S	Neat	C975	04:11	5.4	7	-4
OS017	2001-03-22	ABC-S	Neat	C975	05:35	4.3	5.7	1
OS006	2001-01-29	ABC-S	75/25	C976	01:04	8.0	0.6	-8
OS006	2001-01-29	ABC-S	75/25	C976	01:34	7.2	0.6	-8
OS009	2001-02-06	ABC-S	75/25	C976	01:29	6.1	33	-8
OS009	2001-02-05	ABC-S	75/25	C976	01:45	7.4	33	-8
OS009	2001-02-05	ABC-S	75/25	C976	02:38	4.6	33	-8
OS010	2001-02-06	ABC-S	75/25	C976	02:09	3.3	9	-6
OS011	2001-02-09	ABC-S	75/25	C976	01:06	12.2	19	-8
OS011	2001-02-09	ABC-S	75/25	C976	01:10	12.3	20	-8
OS012	2001-02-10	ABC-S	75/25	C976	01:15	8.0	30	-5
OS013	2001-02-14	ABC-S	75/25	C976	01:46	6.2	3	-5
OS013	2001-02-14	ABC-S	75/25	C976	02:08	5.2	2	-6
OS014	2001-02-14	ABC-S	75/25	C976	01:26	8.7	3	-5
OS014	2001-02-14	ABC-S	75/25	C976	01:32	7.2	7	-5
OS014	2001-02-14	ABC-S	75/25	C976	01:38	5.3	7	-4
OS014	2001-02-14	ABC-S	75/25	C976	01:41	5.2	7	-4
OS017	2001-03-22	ABC-S	75/25	C976	03:50	4.3	5.7	1
OS017	2001-03-22	ABC-S	75/25	C976	02:05	4.7	7.3	0
OS017	2001-03-22	ABC-S	75/25	C976	01:54	5.3	0.2	0
OS005	2001-01-19	ABC-S	50/50	C977	00:53	2.5	21	0
OS013	2001-02-14	ABC-S	50/50	C977	00:31	5.3	3	-5

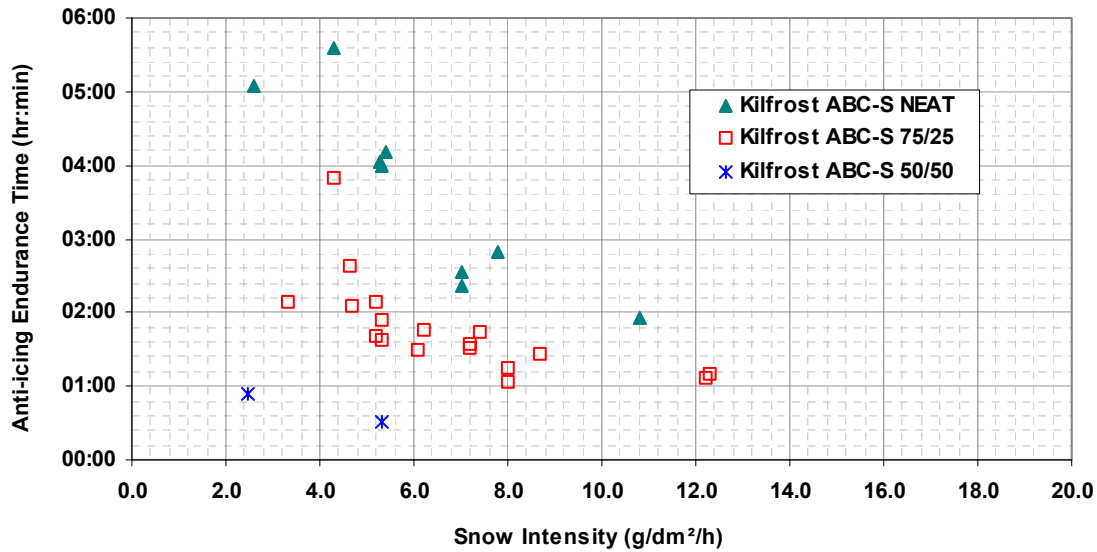


FIGURE 3. ANTI-ICING ENDURANCE TIME VERSUS SNOW INTENSITY FOR KILFROST ABC-S

Figure 3 shows that the anti-icing time decreases as the snow rate increases. The position of the data points on the graph suggests that the anti-icing endurance time could be expressed as a negative power function of the snow intensity. The graph also shows longer times for the neat fluid, followed by the 75/25 dilution, and then the 50/50 dilution.

2.2.2 SPCA AD-480.

Twenty tests were successfully performed on SPCA AD-480-9 on the neat fluid and 11 on the 75/25 dilution. There were no tests performed on the 50/50 dilutions, mainly due to the high freeze point of that dilution. The fluid had to be stored inside to avoid freezing and, therefore, was not equilibrated with the outside air temperature for testing. The results are presented in table 6. A graph comparing snow fall rate and anti-icing endurance time is presented in figure 4.

Figure 4 shows that the anti-icing endurance time decreases as the snow rate increases. The position of the data points on the graph suggests that the anti-icing endurance time could be expressed as a negative power function of the snow rate. The graph also shows longer times for the neat fluid than for the 75/25 dilution.

TABLE 6. OUTDOOR TEST RESULTS—SPCA AD-480

Test No.	Date	Fluid	Dilution	AMIL Code	AET (30% snow) (hr:min)	Average Snow Intensity (g/dm ² /h)	Average Wind Speed (km/h)	Average Air Temperature (°C)
OS009	2001-02-06	AD-480	Neat	E008	02:25	6.6	33	-8
OS009	2001-02-05	AD-480	Neat	E008	03:58	5.2	33	-8
OS010	2001-02-06	AD-480	Neat	E008	05:03	2.7	9	-6
OS011	2001-02-09	AD-480	Neat	E008	01:04	12.3	20	-8
OS011	2001-02-09	AD-480	Neat	E008	01:33	11.1	19	-8
OS013	2001-02-14	AD-480	Neat	E008	04:00	5.3	2	-6
OS014	2001-02-14	AD-480	Neat	E008	02:33	8.0	6	-5
OS014	2001-02-14	AD-480	Neat	E008	03:50	5.3	7	-4
OS017	2001-03-22	AD-480	Neat	E008	05:30	4.3	5.7	1
OS017	2001-03-22	AD-480	Neat	E008	02:59	5.9	4.1	0
OS009	2001-02-05	AD-480	75/25	E008	01:15	7.1	33	-8
OS009	2001-02-05	AD-480	75/25	E008	02:45	4.6	33	-8
OS011	2001-02-09	AD-480	75/25	E008	01:04	12.2	19	-8
OS012	2001-02-10	AD-480	75/25	E008	01:15	8.0	30	-5
OS013	2001-02-14	AD-480	75/25	E008	02:48	5.2	2	-5
OS013	2001-02-14	AD-480	75/25	E008	01:59	4.4	2	-5
OS014	2001-02-14	AD-480	75/25	E008	01:33	8.6	3	-5
OS014	2001-02-14	AD-480	75/25	E008	01:52	6.7	6	-5
OS014	2001-02-14	AD-480	75/25	E008	02:10	5.8	7	-4
OS017	2001-03-22	AD-480	75/25	E008	04:06	5.0	5.7	1
OS017	2001-03-22	AD-480	75/25	E008	02:25	5.0	4.1	0

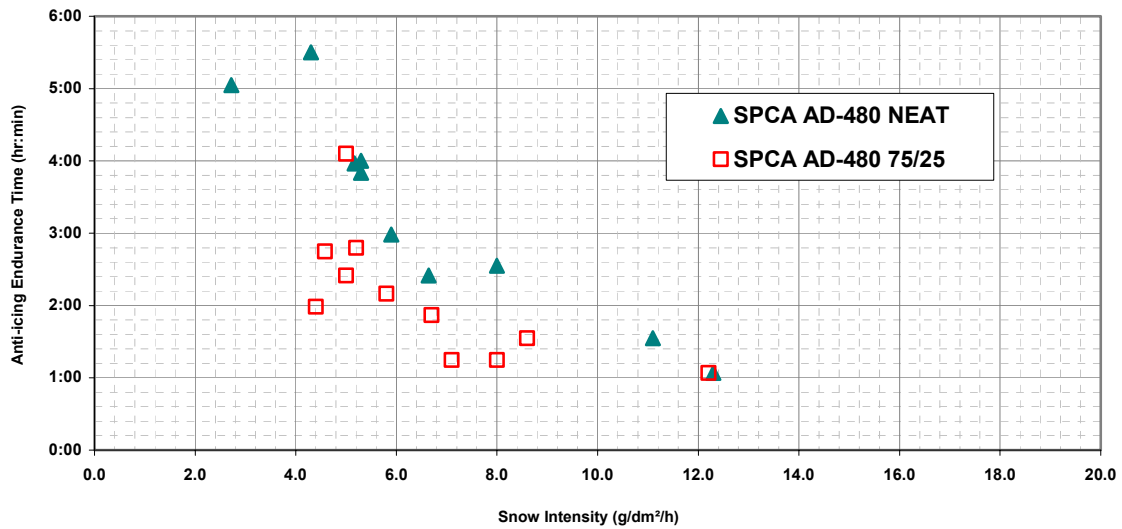


FIGURE 4. ANTI-ICING ENDURANCE TIME VERSUS SNOW INTENSITY FOR SPCA AD-480

2.2.3 Dow Ultra+.

Thirty-two tests were successfully completed with Dow Ultra+. All tests with this fluid were conducted on the neat fluid, since the fluid is not certified or used diluted. The results are presented in table 7. A graph comparing snow fall rate and anti-icing endurance time is presented in figure 5.

TABLE 7. OUTDOOR TEST RESULTS—DOW ULTRA+

Test No.	Date	Fluid	Dilution	AMIL Code	AET (30% snow) (hr:min)	Average Snow Intensity (g/dm ² /h)	Average Wind Speed (km/h)	Average Air Temperature (°C)
OS006	2001-02-29	Ultra +	Neat	C971	00:56	8.3	0.6	-8
OS009	2001-02-05	Ultra +	Neat	C971	01:09	6.6	20-30	-8
OS009	2001-02-06	Ultra +	Neat	C971	01:25	6.7	20-30	-8
OS009	2001-02-05	Ultra +	Neat	C971	01:26	7.0	20-30	-8
OS009	2001-02-06	Ultra +	Neat	C971	01:27	6.5	20-30	-8
OS009	2001-02-05	Ultra +	Neat	C971	01:36	6.9	20-30	-8
OS009	2001-02-05	Ultra +	Neat	C971	02:03	4.8	20-30	-8
OS010	2001-02-06	Ultra +	Neat	C971	03:11	2.5	7	-6
OS010	2001-02-06	Ultra +	Neat	C971	03:15	2.5	7	-6
OS011	2001-02-09	Ultra +	Neat	C971	00:58	12.2	20	-8
OS011	2001-02-09	Ultra +	Neat	C971	01:03	12.2	19	-8
OS011	2001-02-09	Ultra +	Neat	C971	01:12	11.4	19	-8
OS011	2001-02-09	Ultra +	Neat	C971	01:13	13.0	20	-8
OS012	2001-02-10	Ultra +	Neat	C971	01:22	7.0	30	-5
OS012	2001-02-10	Ultra +	Neat	C971	01:52	6.4	30	-5
OS013	2001-02-14	Ultra +	Neat	C971	01:28	6.4	2	-4
OS013	2001-02-14	Ultra +	Neat	C971	01:47	6.0	2	-4
OS013	2001-02-14	Ultra +	Neat	C971	02:08	5.2	1.5	-7
OS013	2001-02-14	Ultra +	Neat	C971	02:08	5.2	1.5	-7
OS014	2001-02-14	Ultra +	Neat	C971	01:24	7.2	7	-5
OS014	2001-02-14	Ultra +	Neat	C971	01:24	7.2	7	-5
OS014	2001-02-14	Ultra +	Neat	C971	01:26	8.3	5	-5
OS014	2001-02-14	Ultra +	Neat	C971	01:21	8.3	5	-5
OS014	2001-02-14	Ultra +	Neat	C971	01:30	6.2	1	-5
OS014	2001-02-14	Ultra +	Neat	C971	01:49	5.8	1	-5
OS014	2001-02-14	Ultra +	Neat	C971	02:00	4.1	7	-4
OS014	2001-02-14	Ultra +	Neat	C971	02:02	4.1	7	-4
OS017	2001-03-22	Ultra +	Neat	C971	03:49	5.0	5.0	0.8
OS017	2001-03-22	Ultra +	Neat	C971	03:49	5.0	5.0	0.8
OS017	2001-03-22	Ultra +	Neat	C971	02:18	5.1	6.1	0.3
OS017	2001-03-22	Ultra +	Neat	C971	02:21	5.1	6.1	0.3

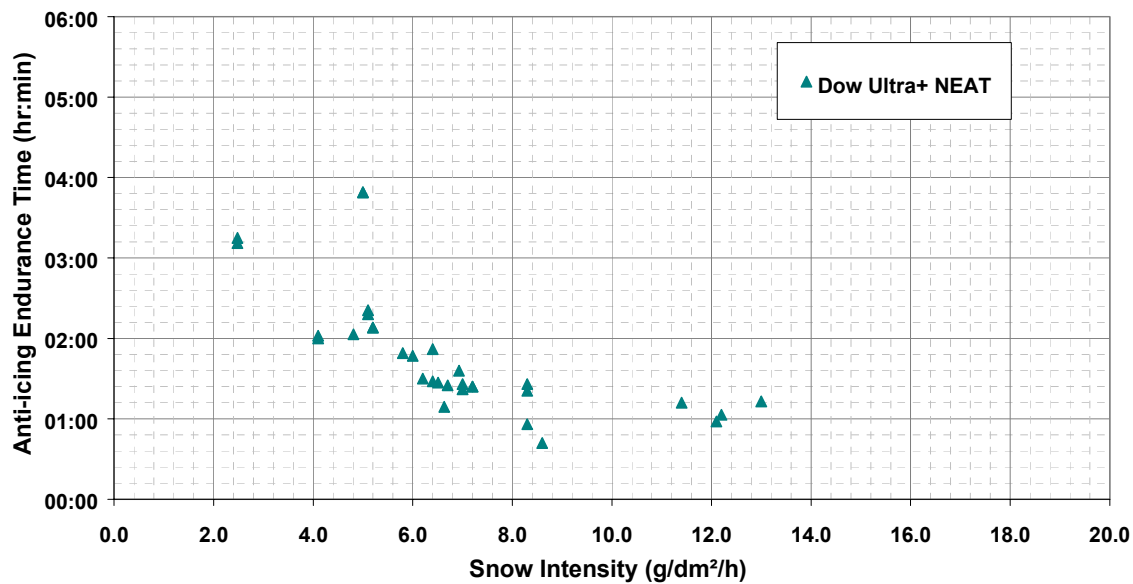


FIGURE 5. ANTI-ICING ENDURANCE TIME VERSUS SNOW INTENSITY FOR DOW ULTRA+

Figure 5 shows that the anti-icing endurance time decreases as the snow rate increases. As in the case of the other two fluids, the general distribution of the data points on the graph suggests that the anti-icing endurance time could be expressed as a negative power function of the snow rate.

2.3 OUTDOOR TEST RESULTS—DATA FROM ALL SITES.

Similar tests were performed at two other sites, Dorval in Montreal, run by APS Aviation, and Boulder, Colorado, run by the NCAR, in order to compare results. Prior to starting the tests, the same procedure and failure call was agreed upon. The site in Dorval was visited by AMIL personnel to compare failure call.

2.3.1 Kilfrost ABC-S, Outdoor Data From All Sites.

Figures 6 through 8 show a comparison of the results of the three test sites on Kilfrost ABC-S neat, 75/25, and 50/50 dilutions, respectively. In general, the graphs show a good correlation between test sites. The APS site had more snow events at the higher intensities, which is helpful to extend the range of the data. NCAR had three data points: two for ABC-S neat and one for the 75/25 dilution. These anti-icing endurance times tended to be shorter than the values measured by the other two sites, but are within range. In all cases, the combined data from the three sites further suggests a negative power law distribution.

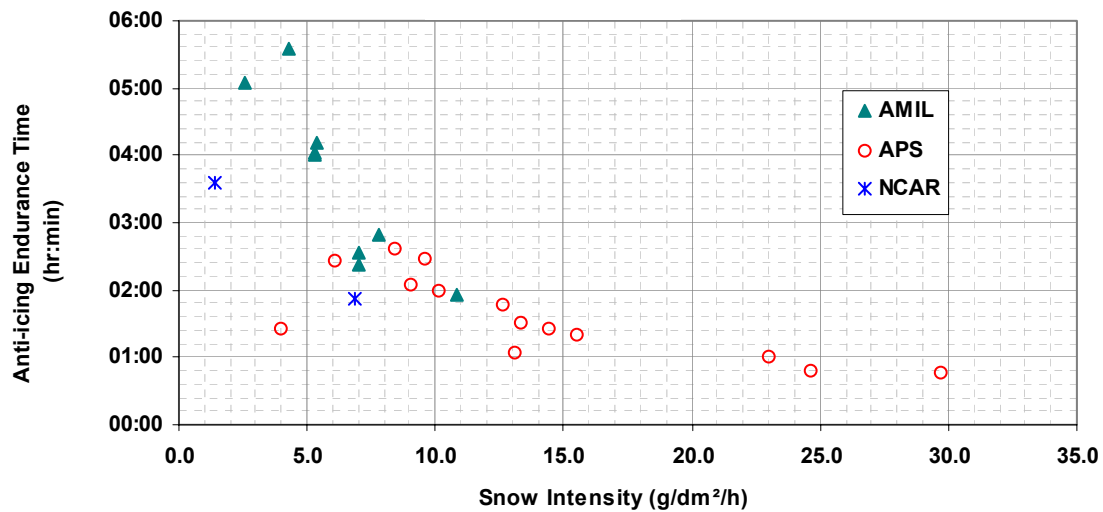


FIGURE 6. COMPARISON OF OUTDOOR DATA FROM THE THREE TEST SITES FOR KILFROST ABC-S NEAT FLUID

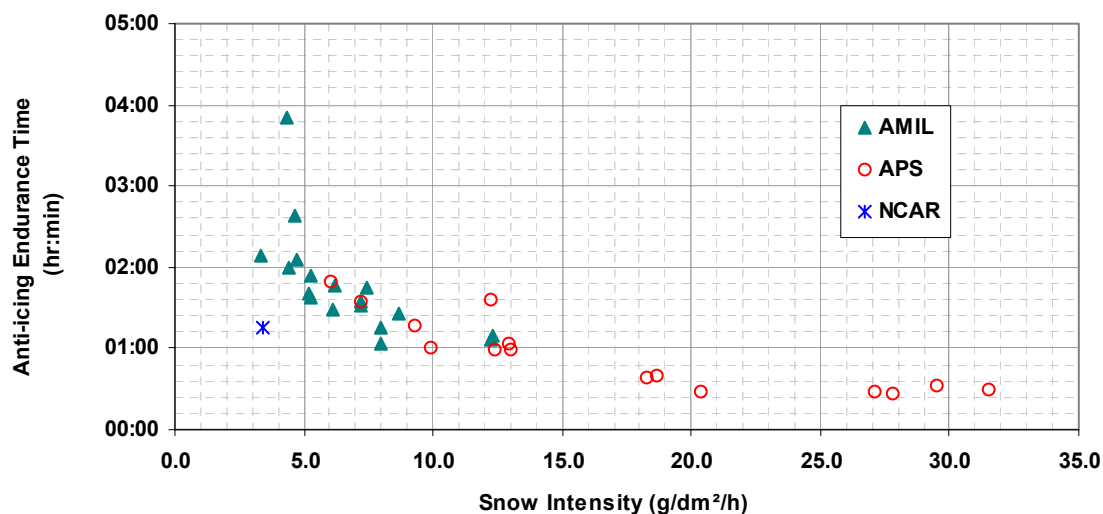


FIGURE 7. COMPARISON OF OUTDOOR DATA FROM THE THREE TEST SITES FOR KILFROST ABC-S 75/25 DILUTION

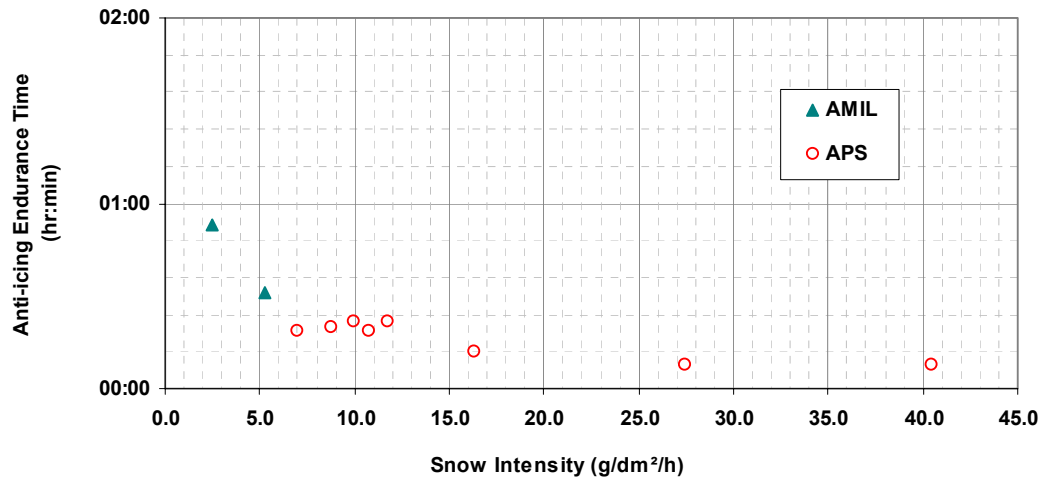


FIGURE 8. COMPARISON OF OUTDOOR DATA FROM THE THREE TEST SITES FOR KILFROST ABC-S 50/50 DILUTION

2.3.2 SPCA AD-480, Outdoor Test Data From All Sites.

Figures 9 through 11 show a comparison of the results of the three test sites on SPCA AD-480 neat, 75/25, and 50/50 dilutions, respectively. In general, the graphs show a good correlation between test sites. Again, APS had more data in the higher precipitation rates, which was complimentary to the AMIL data. NCAR had only four data points for the neat fluid and none for the dilutions. Only APS had data for the 50/50 dilution. In the case of the neat fluid, figure 9, all the points follow the negative power trend with the exception of two points of APS at 5 and 1 g/dm²/h, which fall outside the trend with very short endurance times. The NCAR points have shorter endurance times than the general trend, but are within range.

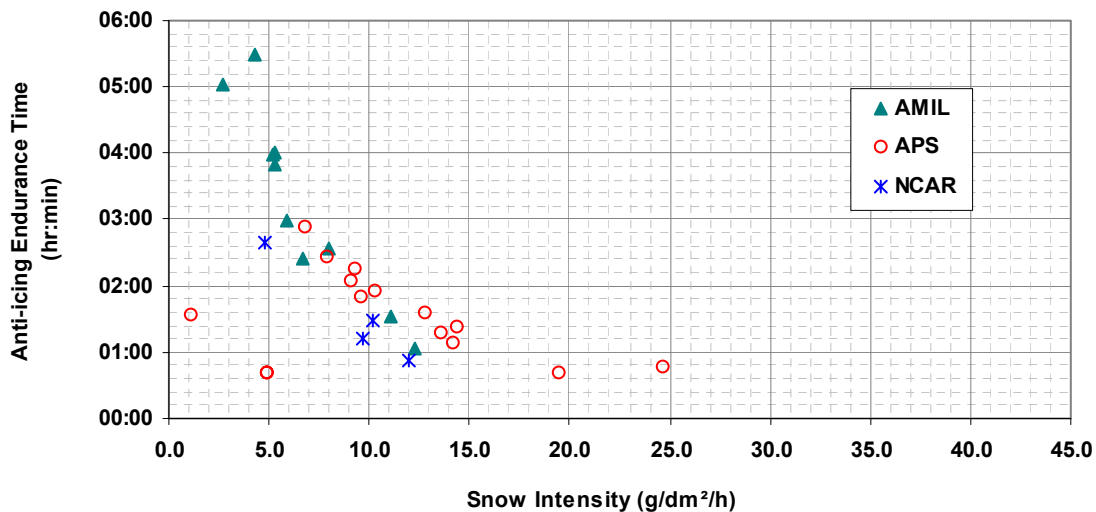


FIGURE 9. COMPARISON OF OUTDOOR DATA FROM THE THREE TEST SITES FOR SPCA AD-480 NEAT FLUID

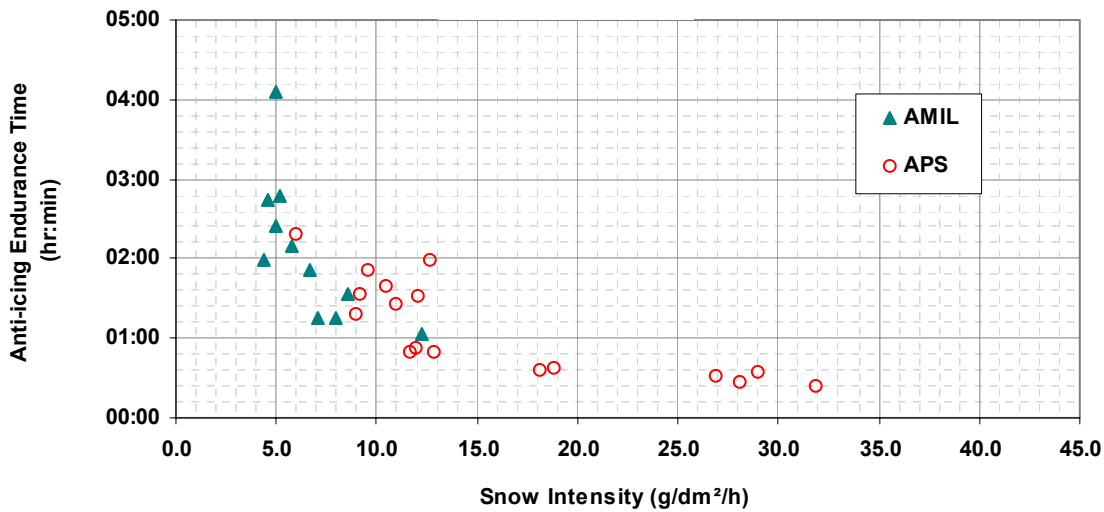


FIGURE 10. COMPARISON OF OUTDOOR DATA FROM THE THREE TEST SITES FOR SPCA AD-480 75/25 DILUTION

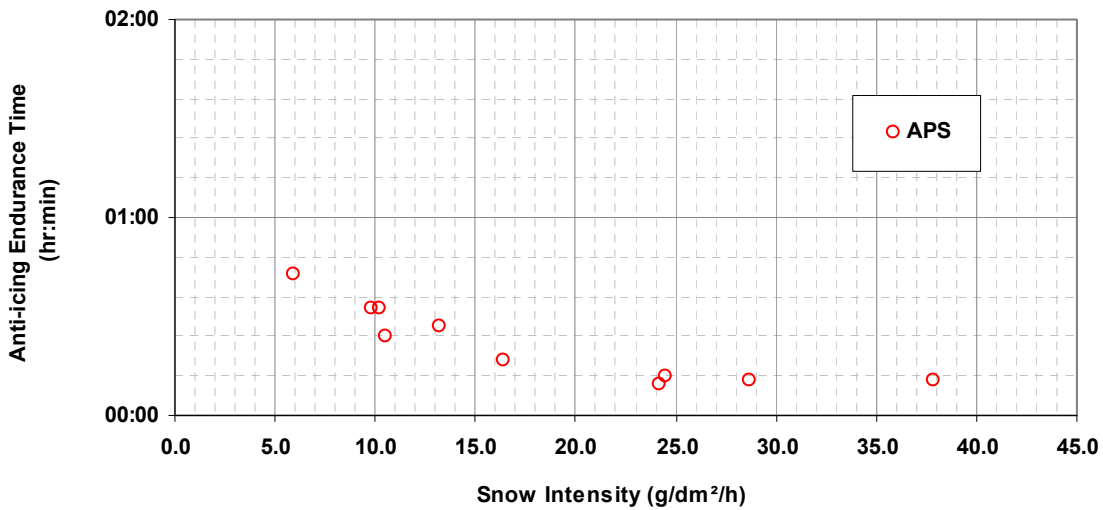


FIGURE 11. COMPARISON OF OUTDOOR DATA FROM THE THREE TEST SITES FOR SPCA AD-480 50/50 DILUTION

2.3.3 Dow Ultra+, Outdoor Test Data From All Sites.

Figure 12 shows a comparison of the results of the three test sites on Dow Ultra+. The graph shows that, in general, there is a good correlation between test sites. Again, the APS site had more events at the higher intensities to extend the range of the data. NCAR had only one data point for this fluid, but it fit well with the data from the other two sites. As with the other fluid dilutions, the data suggests a negative power law distribution.

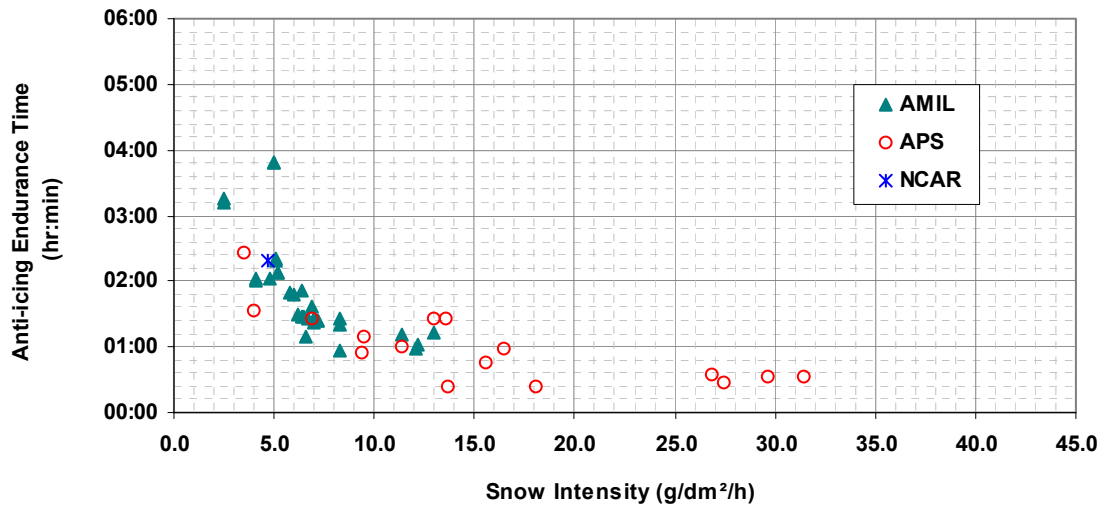


FIGURE 12. COMPARISON OF OUTDOOR DATA FROM THE THREE TEST SITES FOR DOW ULTRA+ NEAT

2.4 CONFIDENCE INTERVALS—OUTDOOR DATA.

A mathematical regression analysis of the data was made in order to compare and ascertain the uncertainty involved before comparing the indoor data. The regression analysis was made using existing excel macro commands and a negative power law according to the equation:

$$t = aI^{-b} \quad (1)$$

where:

- t = anti-icing endurance time
- I = snow intensity
- a, b = constants to be determine for each fluid and dilution

The same program was used to generate confidence intervals. They were generated to determine the variation and error envelope in order to compare it with the indoor data. Any data generated may not fall on the actual regression line, as the outdoor data does not, but it should fall within the confidence intervals.

2.4.1 Kilfrost ABC-S Neat Confidence Intervals for Outdoor Data.

For the outdoor data of Kilfrost ABC-S neat, a regression analysis with confidence intervals was performed and is presented in figure 13. For the regression analysis, two points were excluded and are pointed out in figure 13. Both points represent light snow events at colder temperatures, -14° and -17°C, which may account for their shorter anti-icing endurance times at their low intensities. If those points were taken into account, the confidence intervals would be wider and would not help to compare it with indoor data.

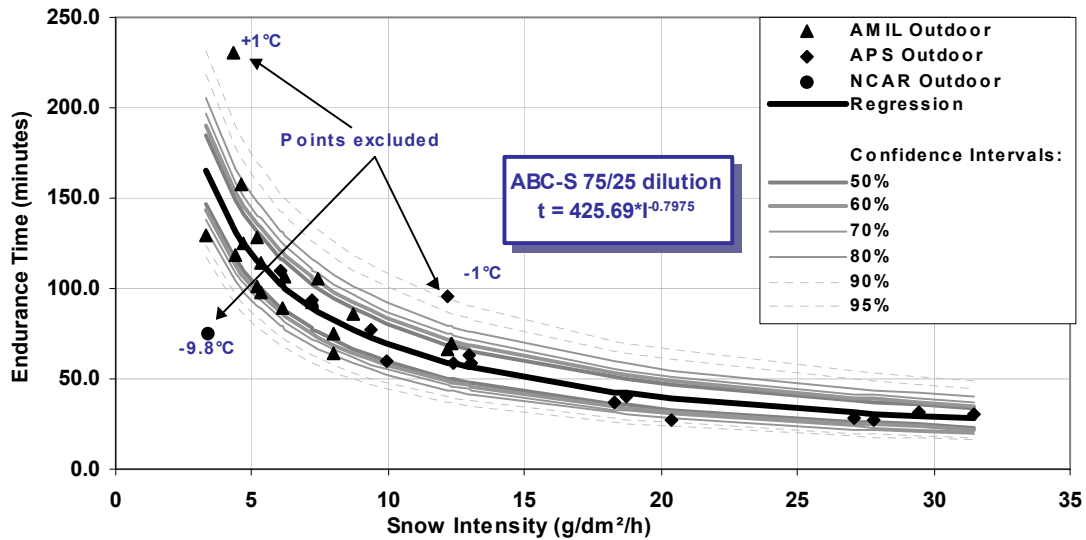


FIGURE 13. KILFROST ABC-S NEAT OUTDOOR DATA WITH REGRESSION ANALYSIS AND CONFIDENCE INTERVALS

2.4.2 Kilfrost ABC-S 75/25 Dilution Confidence Intervals for Outdoor Data.

Figure 14 shows the regression analysis with confidence intervals for Kilfrost ABC-S 75/25 dilution. For this analysis, three data points were excluded, one from each test site, which did not closely fit with the other data. The points are identified in figure 14. One point was generated with a cold temperature of -9.8°C, having a shorter anti-icing endurance time than expected, and two points generated at warmer, +1° and -1°C, temperatures had longer endurance times than most of the data.

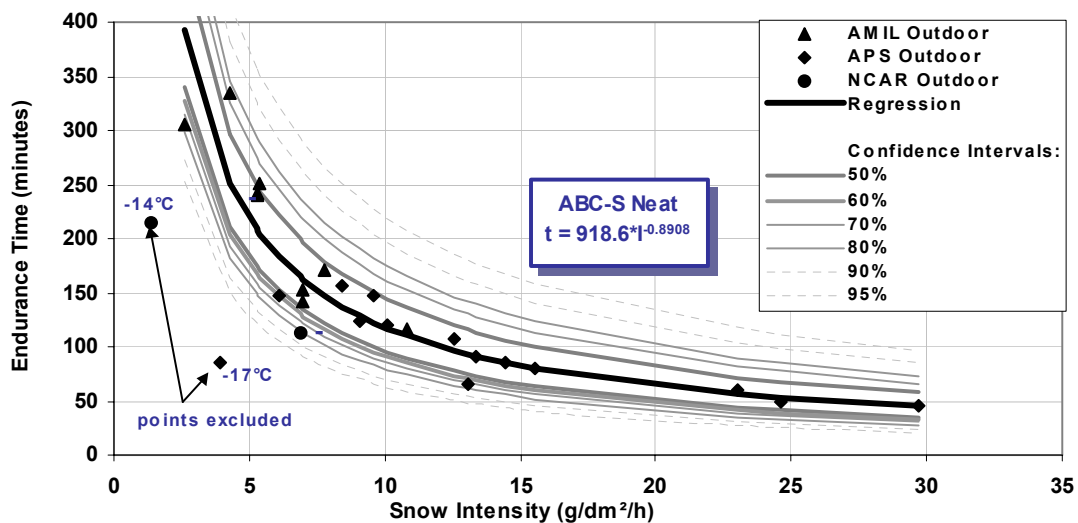


FIGURE 14. KILFROST ABC-S 75/25 DILUTION OUTDOOR DATA REGRESSION ANALYSIS AND CONFIDENCE INTERVALS

2.4.3 Kilfroast ABC-S 50/50 Dilution Confidence Intervals for Outdoor Data.

Figure 15 shows the regression analysis with confidence intervals for Kilfroast ABC-S 50/50 dilution. For this analysis, all data points were included.

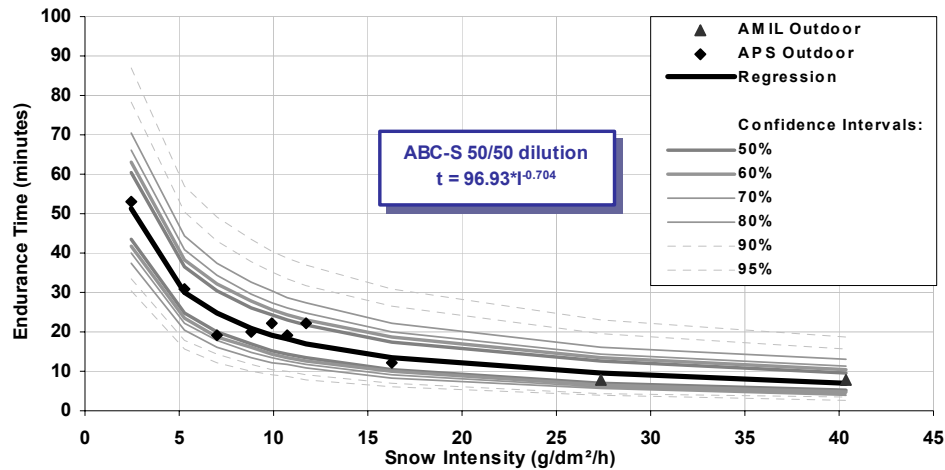


FIGURE 15. KILFROAST ABC-S 50/50 DILUTION OUTDOOR DATA WITH REGRESSION ANALYSIS AND CONFIDENCE INTERVALS

2.4.4 SPCA AD-480 Neat Confidence Intervals for Outdoor Data.

Figure 16 shows a regression analysis with confidence intervals for SPCA AD-480 neat. For this analysis, two data points from the APS test site, which did not closely fit with the other data, were excluded. The points are identified in figure 16. Both points were for light snow intensities at colder temperatures, -14° and -17°C, and have shorter endurance times than the rest of the data.

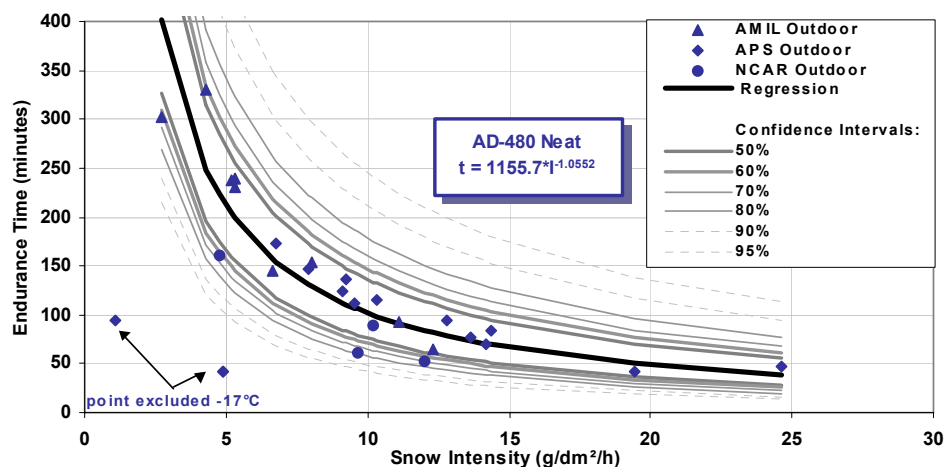


FIGURE 16. SPCA AD-480 NEAT OUTDOOR DATA WITH REGRESSION ANALYSIS AND CONFIDENCE INTERVALS

2.4.5 SPCA AD-480 75/25 Dilution Confidence Intervals for Outdoor Data.

Figure 17 shows a regression analysis with confidence intervals for SPCA AD-480 75/25 dilution. For this analysis, one data point from the AMIL site, which did not closely fit with the other data, was excluded. The point is identified in figure 17. This point was generated at a warmer temperature, +1°C, than the other points, which may account for its longer endurance time.

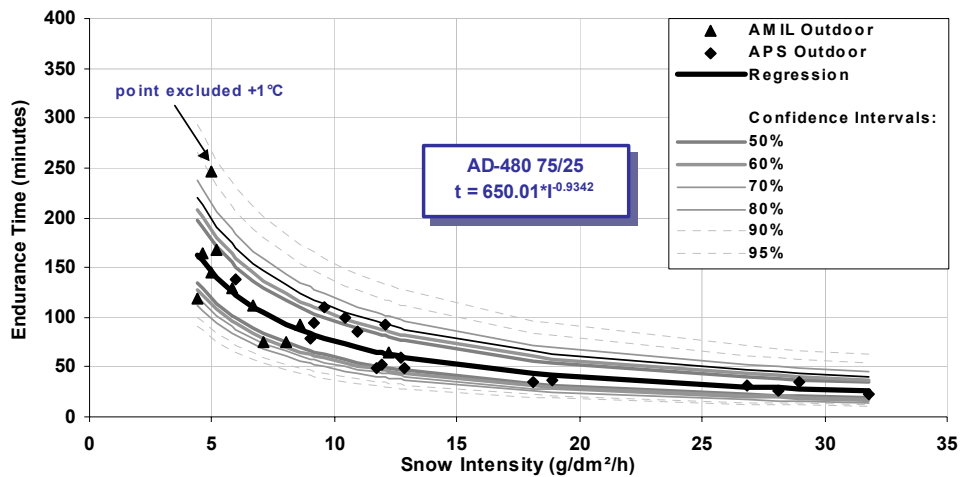


FIGURE 17. SPCA AD-480 75/25 DILUTION OUTDOOR DATA WITH REGRESSION ANALYSIS AND CONFIDENCE INTERVALS

2.4.6 SPCA AD-480 50/50 Dilution Confidence Intervals for Outdoor Data.

Figure 18 shows a regression analysis with confidence intervals for SPCA AD-480 50/50 dilution. For this analysis, all data points were considered.

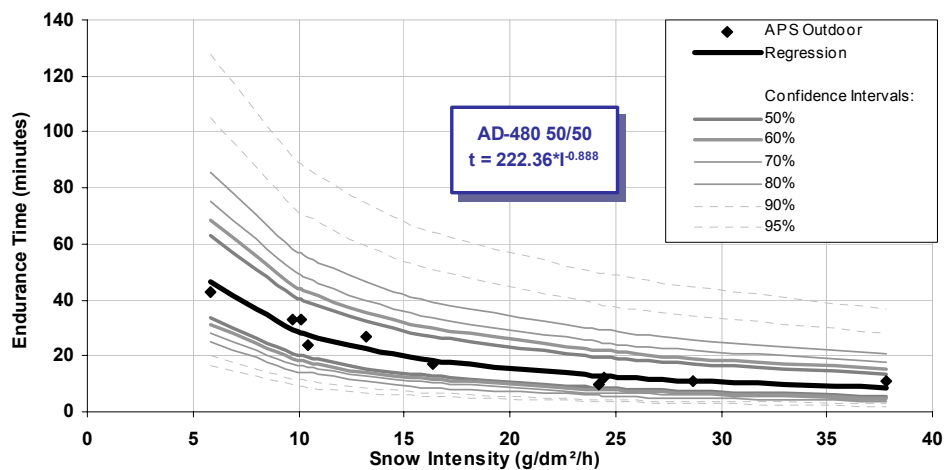


FIGURE 18. SPCA AD-480 50/50 DILUTION OUTDOOR DATA WITH REGRESSION ANALYSIS AND CONFIDENCE INTERVALS

3. INDOOR TESTS.

3.1 INDOOR TEST PROCEDURE.

At AMIL, the snow tests are carried out in two steps: (1) the artificial snow is made and collected in a cold chamber and (2) the snow is evenly distributed over the test plate as described below.

3.1.1 Snow Making.

The artificial snow was made in a cold chamber by means of a pneumatic water spray nozzle supplied with water and compressed air. The nozzle produces a spray of very fine water droplets which become supercooled in cold air and freeze to form solid ice crystals on contact with a collection plate on the chamber floor. Water flow and air pressure are adjusted to obtain a snow density of 0.1 g/cm³.

- Air temperature: -20°C ±5
- Water droplet size: 22µm MVD ±3
- Water flow rate to nozzle: 70 mL/minute
- Air pressure to nozzle: 260 kPa

3.1.2 Snow Storage.

The laboratory-made snow is placed in an insulated container, which is stored in a freezer that is kept at a temperature below -10°C. The snow quality is verified prior to each test by means of a density measurement. Furthermore, if the artificial snow shows any evidence of sintering, agglomeration, or crystallization, it is not used for the snow tests.

3.1.3 Snow Distribution System.

For the indoor snow tests, the snow is distributed as ice particles in the form of clusters in the range of the targeted intensities. The snow distribution system is designed so that the mass of each cluster is 0.10 g or less. The snow is placed in a u-shaped aluminum box, 320 mm long, 253 mm high, and 132 mm wide at the top, with a 65-mm-high drawer at the top with a sliding base, which allows the addition of snow in between tests (figure 19). The box is suspended from a track around 760 mm above the center of the test plate (figure 20). The track is attached to a motor which provides the lateral movement of the snow box. The lateral displacement speed depends on the desired snow intensity. The snow is continually stirred inside the box by means of a rotating system consisting of three blades disposed at 120° angles from each other (figure 21). Each blade measures 50 x 300 mm and consists of a frame housing a wire mesh. The continued rotation of the blades prevents clumping of the snow prior to dispensing. The box contains an opening at the base, 10 mm wide along the length of the box. This opening houses a 32-mm-diameter Acetal cylinder which contains 18 cavities arranged in six rows of three cavities each at 60° spacing (figure 22). Each cavity has a diameter of 11 mm and is hollowed to a u-shape. The cavities on each row are spaced at 87-mm intervals and out of phase with its neighboring row. The cylinder turns after a given time interval, thus, dispensing snow clusters

onto the test plate. The rotation speed of the cylinder is predefined to accommodate the desired snow intensity.

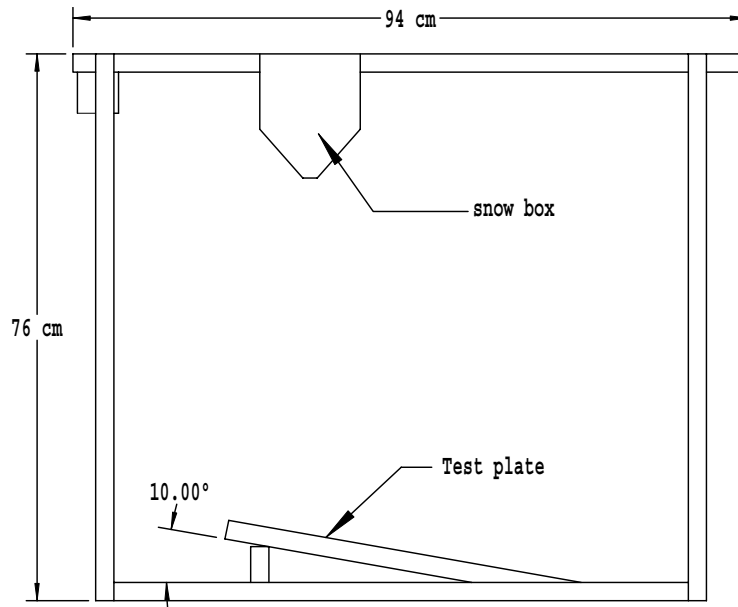


FIGURE 19. SNOW BOX MOUNTED IN ITS SUPPORT ABOVE THE TEST PLATE

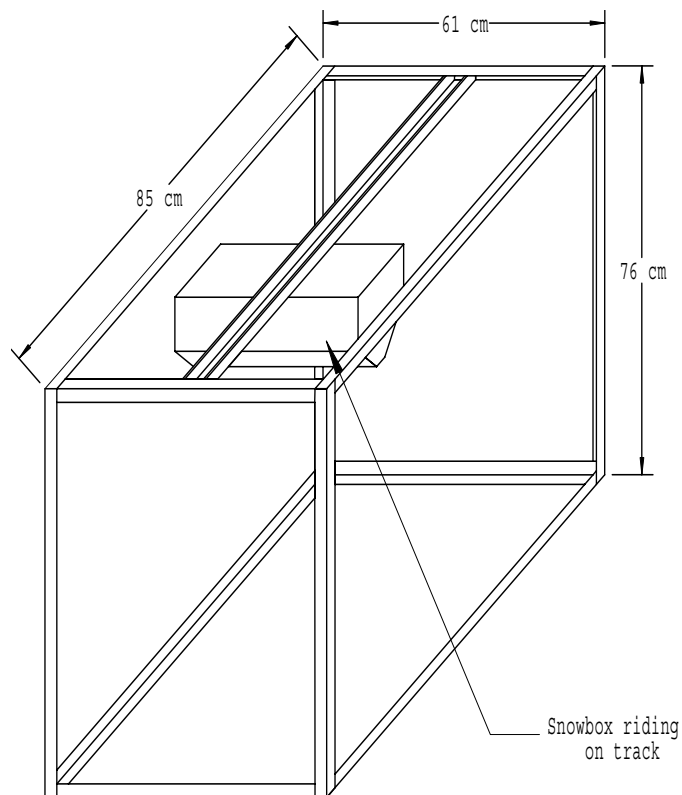


FIGURE 20. SNOW BOX ON TRACK OF SUPPORT

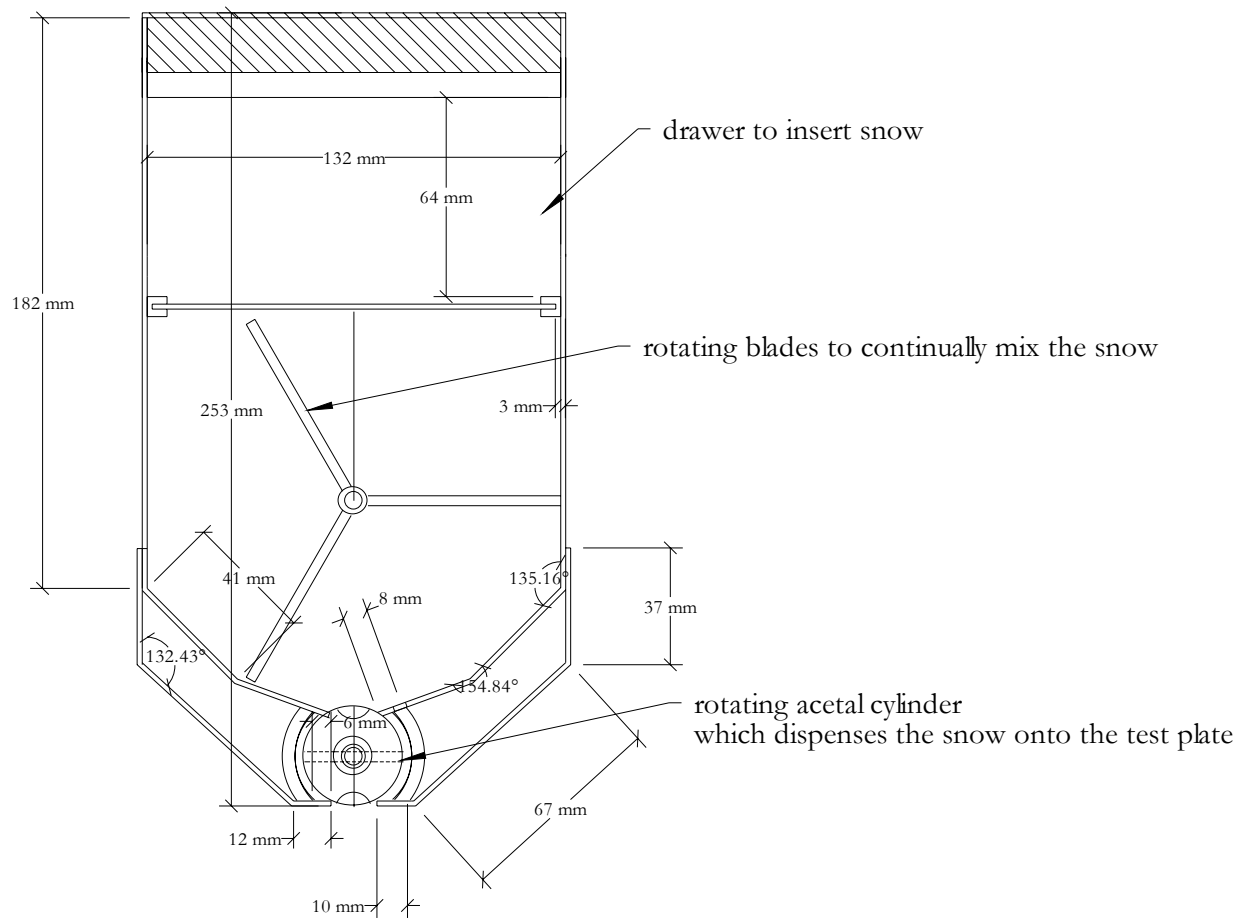


FIGURE 21. CROSS SECTION OF SNOW BOX

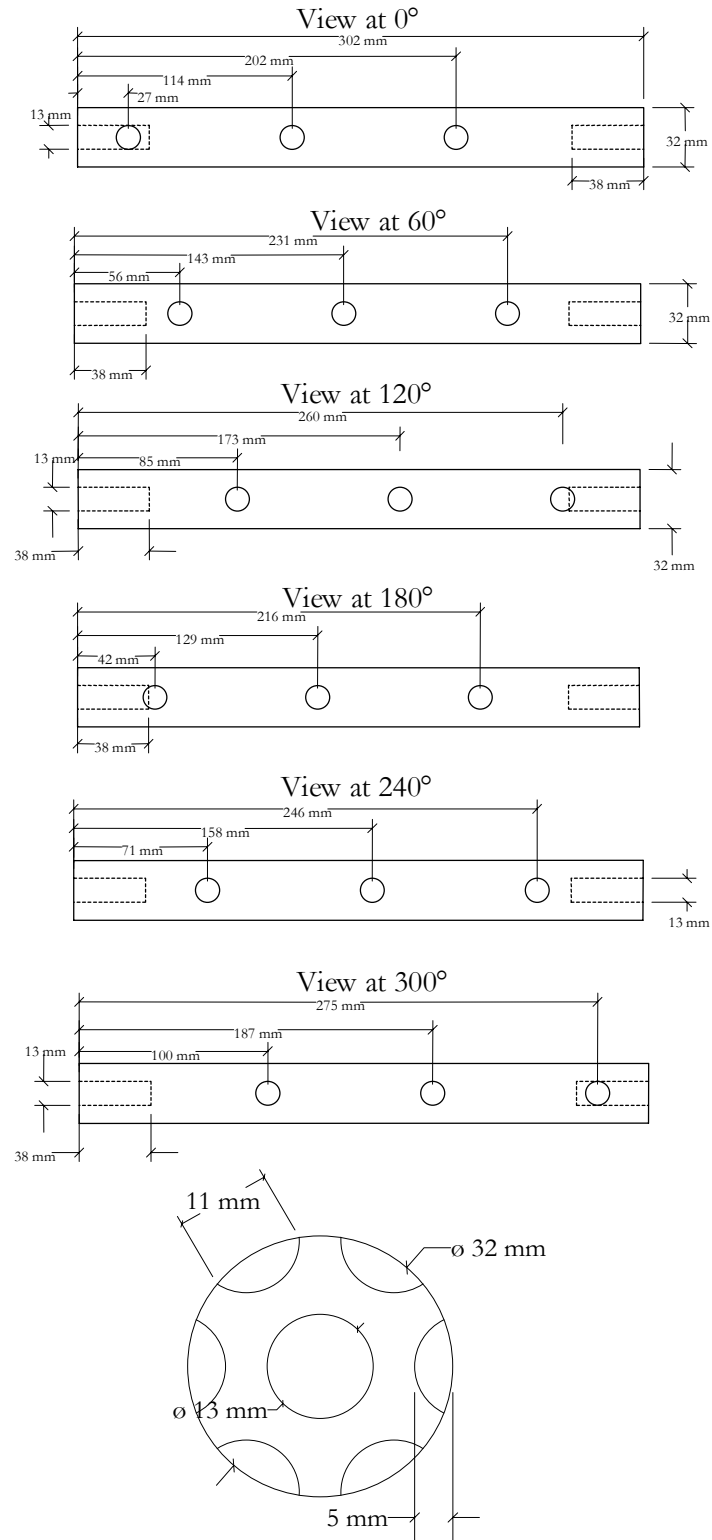


FIGURE 22. SIDE VIEWS AND CROSS SECTION OF ACETAL CYLINDER WITH SIX ROWS OF THREE CAVITIES WHICH DISPENSES THE SNOW FROM THE BOX TO THE TEST PLATE

3.2 INDOOR TEST RESULTS.

Initially, the indoor tests consisted of replicating the conditions of the outside, with respect to temperature and snow intensity. Since discrepancies between indoor and outdoor test results were known, certain additional parameters were examined.

- The first parameter was failure call and procedure. This was addressed by visiting the other test sites, having a common procedure between test sites, and running out door tests at AMIL. Therefore, this parameter has already been addressed in the proceeding sections.
- The second parameter investigated was artificial versus natural snow, i.e., is the artificial snow harder or easier for the fluid to dissolve. This was the first parameter investigated indoors and was made by inserting natural snow in the AMIL snow distribution machine.
- The third parameter investigated was snow cluster size. Tests were run with different cylinders, which had varying numbers and sizes of cavities.
- The final parameter investigated included the effect of wind on the plate temperature. This was addressed outside by recording the air and plate temperature outside and inside in real-time for comparison.

3.2.1 Artificial Versus Natural Snow.

The first of the factors examined was the ability of the fluids to absorb artificial snow as opposed to natural snow. For the indoor tests at AMIL, the snow is artificially made in a cold chamber with a pneumatic water spray and a cold room below -20°C. This results in fine artificial rime particles. Since there were discrepancies between the indoor and outdoor test results, one of the obvious suspects was the type of snow. Is this artificial snow more difficult for the fluids to absorb than the natural snow, which would result in shorter times indoors?

This investigation consisted of collecting natural snow outside and placing it into the AMIL snow distribution box, instead of using artificially made snow. Special care was taken in collecting the cleanest and most pristine snow from outside. Few tests were performed with the natural snow because of the time restrictions. There was no fresh snow outdoors in Chicoutimi, Quebec, after early March.

3.2.1.1 ABC-S 75/25 Dilution, Indoor Tests Artificial Versus Natural Snow.

For Kilfrost ABC-S, only one test was performed using natural snow, and using the 75/25 dilution. The results, compared to the outdoor data and similarly tested indoor data, is presented in figure 23. This graph shows no significant difference between the indoor data obtained with the natural snow and the artificial snow. In fact, the data point falls in the middle of the other indoor data points.

The graph also shows that the indoor data correlates well with the data obtained outdoors, with all the data falling between the upper 50% and the lower 95% confidence intervals.

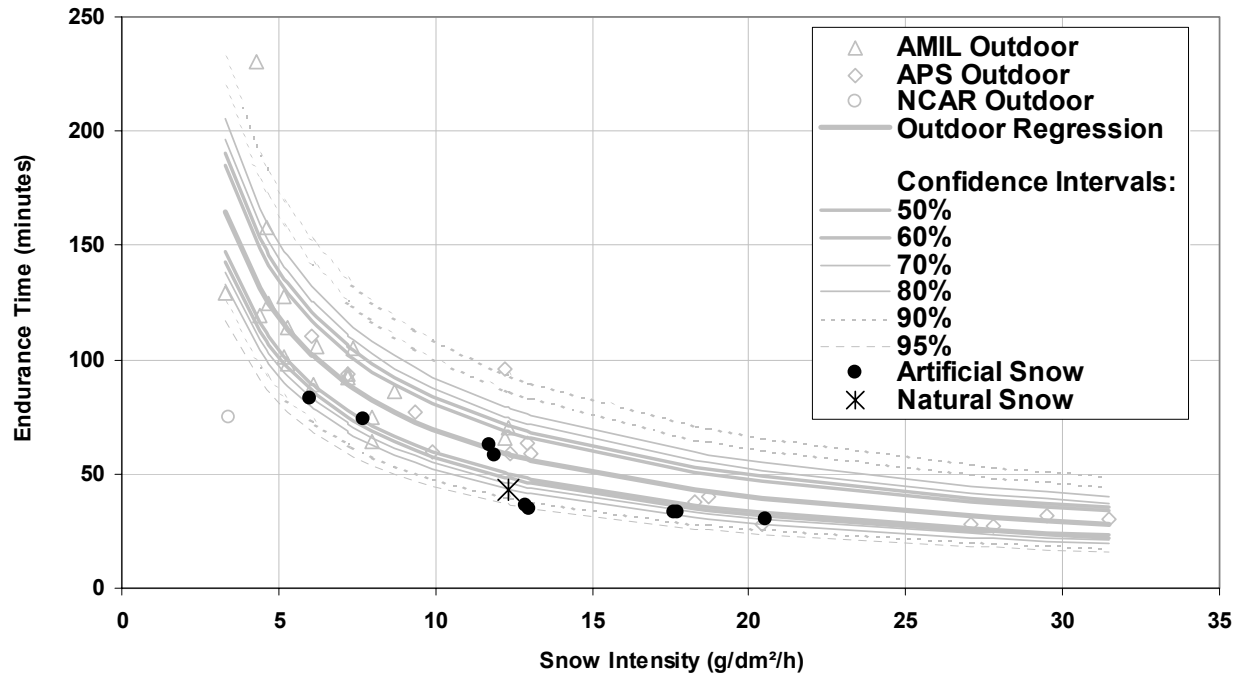


FIGURE 23. ARTIFICIAL VERSUS NATURAL SNOW, KILFROST ABC-S 75/25 DILUTION

3.2.1.2 SPCA AD-480, Indoor Tests Artificial Versus Natural Snow.

For SPCA AD-480 neat, one test was performed using natural snow collected outside. The result is presented in figure 24, along with the outdoor data and indoor data collected using the same method. The one data point gave nearly the same result as a point similarly obtained with artificial snow, and in general, follows the trend of the other indoor data.

This graph also shows a good correlation between indoor and outdoor data with all the indoor data falling between the regression line and the lower 80% confidence interval.

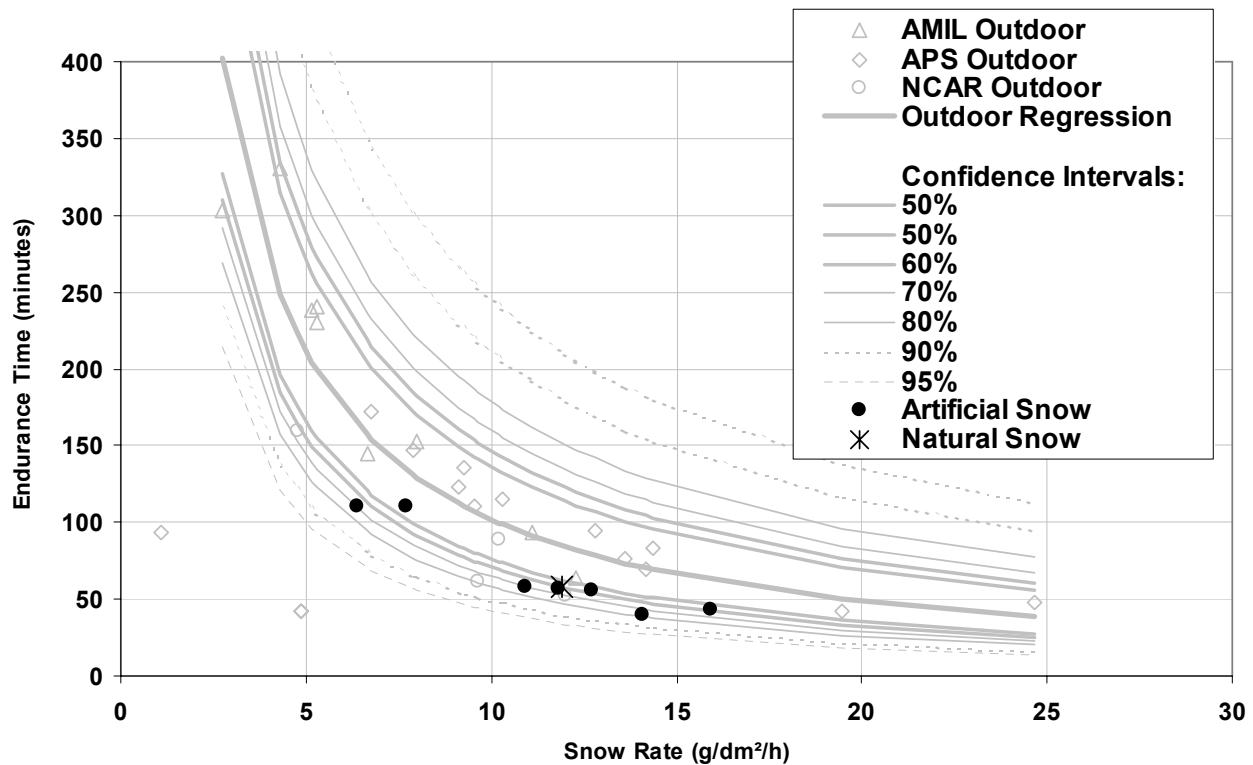


FIGURE 24. SPCA AD-480 NEAT, ARTIFICIAL VERSUS NATURAL SNOW

3.2.1.3 SPCA AD-480 75/25 Dilution, Artificial Versus Natural Snow.

For SPCA AD-480 75/25 dilution, one test was performed using natural snow collected outside. The result is presented in figure 25, along with the outdoor data and indoor data collected using the same method. One data point had nearly the same endurance time as a point obtained with artificial snow.

This graph also shows a good correlation between indoor and outdoor data with all the indoor data falling between the regression line and the lower 95% confidence interval.

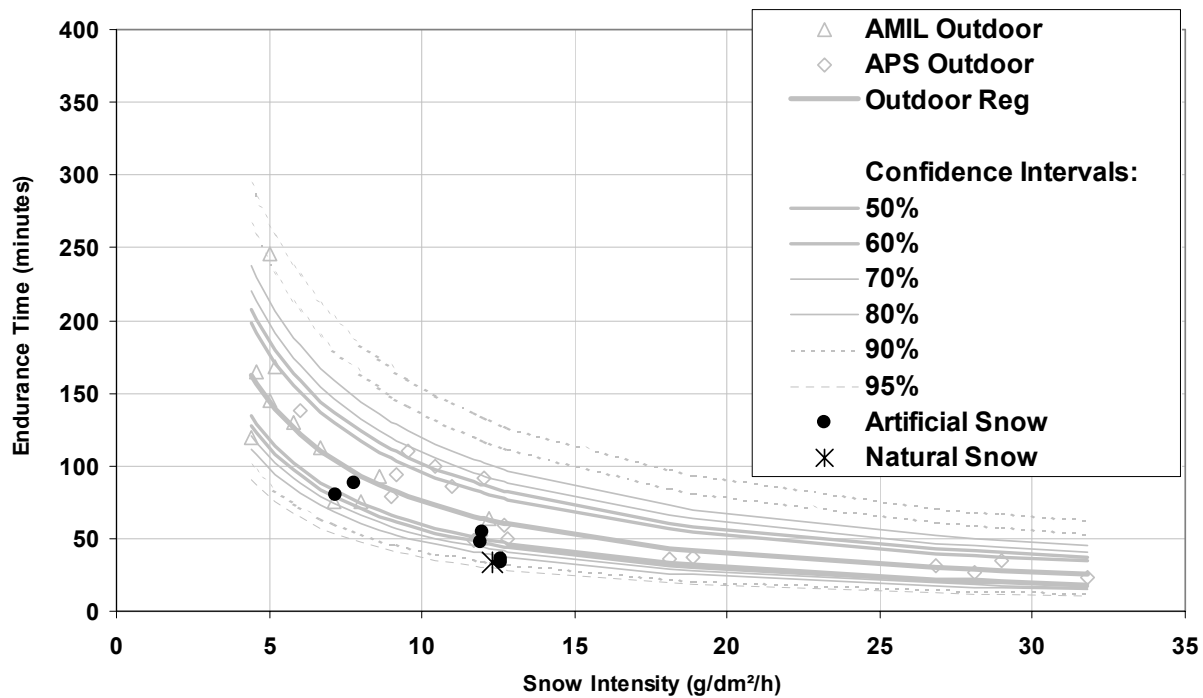


FIGURE 25. SPCA AD-480 75/25 DILUTION, ARTIFICIAL VERSUS NATURAL SNOW

3.2.1.4 Dow Ultra+, Artificial Versus Natural Snow.

For Dow Ultra+, one test was performed using natural snow collected outside. The result of this test is presented in figure 26, along with the outdoor data and indoor data collected using the same method. The one data point, in general, follows the trend of the other indoor data.

This graph also shows a good correlation between indoor and outdoor data with all the indoor data falling between the regression line and slightly above the upper 95% confidence interval. Contrary to the other fluids, which tended to be a bit on the lower side of the regression line, the values of Dow Ultra+ tended to be above the regression line.

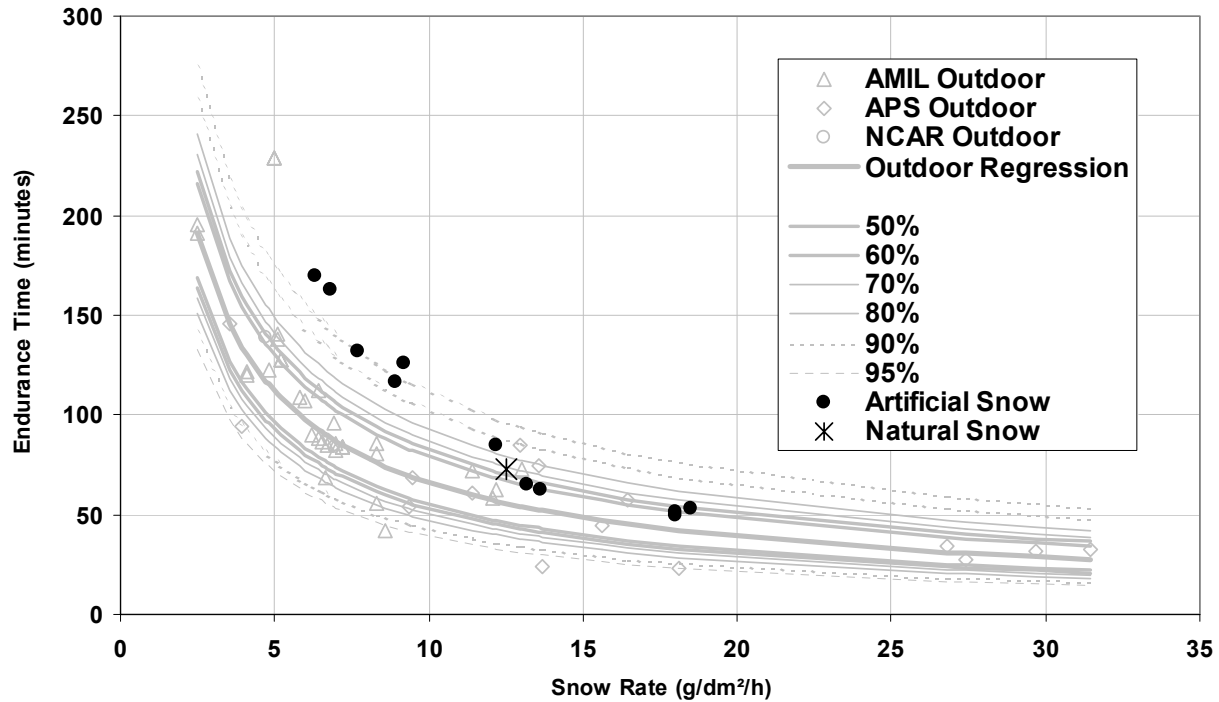


FIGURE 26. DOW ULTRA+, ARTIFICIAL VERSUS NATURAL SNOW

3.2.2 Snow Cluster Size.

An investigation was pursued as to whether the size of the snow cluster had an effect on the endurance time of the fluids. As outlined in section 3.1.3, the AMIL snow distribution machine dispenses the snow in discrete snow clusters via cavities on the cylinder at the base of the machine. The original cylinder consisted of six rows of 3 cavities each, for a total of 18 cavities, with a diameter of 12 mm and a depth of 4.75 mm. Questions arose as to whether this represented an unnaturally severe condition, since the snow falls as clusters of snow grains and not as discrete flakes. Originally, the machine was purposefully designed to replicate a severe condition [5]. However, priorities changed within the SAE group. Therefore, a new cylinder was designed with smaller cavities, consisting of six rows of 6 cavities each, for a total of 36 cavities, with a diameter of 10.8 mm and a depth of 3.0 mm, to see whether the cluster size had an impact on the endurance time of the fluids. Figure 27 shows an example with Kilfrost ABC-S neat indoor tests with the two different cluster sizes. No notable difference was seen with the cluster size and the ability of the fluids to absorb the snow. The tests with the smaller clusters had failures, which appeared more realistic, further resembling the outdoor tests. For the higher intensity tests, the higher rates were more easily obtainable with the cylinder with smaller cavities. Therefore, for this study, the cluster sizes were interchanged. In general, the small cluster was used for the higher intensities, above about 12 g/dm²/h, and the larger clusters for tests below this value.

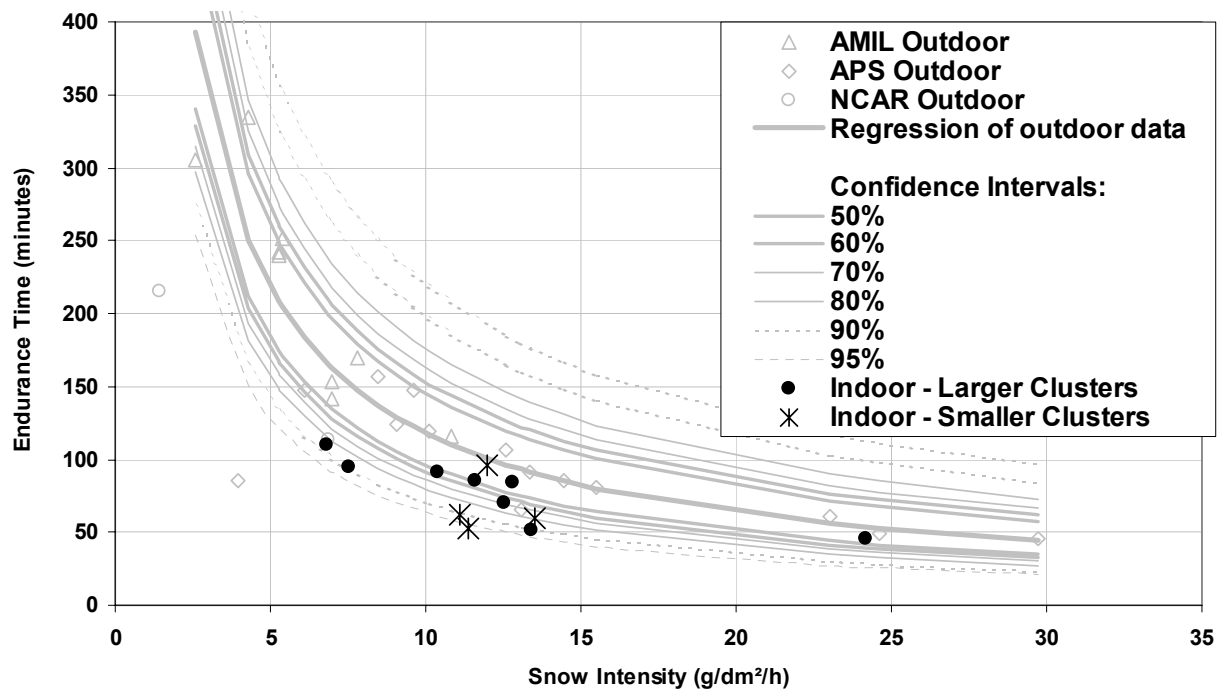


FIGURE 27. SNOW CLUSTER SIZE COMPARISON, ABC-S NEAT

3.2.3 Failure Call.

One of the aspects studied for this series of tests was the failure call. Outside, with all three fluids and dilutions, the failure appeared as a front of white snow (figure 28). The failure was then called once this front covered 30% of the test plate. Inside, this 30% coverage rarely started from the top of the plate. The 30% would more often present itself as patches over the test plate (figure 29). Furthermore, it would initially present itself as 30% slush and later become white snow, as the fluid could no longer absorb the snow. This 30% slush was rarely seen outside, and when seen, it was immediately followed by a white snow failure.



FIGURE 28. EXAMPLES OF OUTDOOR FLUID FAILURE AS A 30% WHITE SNOW FRONT



FIGURE 29. EXAMPLES OF FLUID FAILURE INSIDE AS 30% WHITE SNOW

3.2.3.1 Kilfrost ABC-S Neat, Differences in Failure Call.

Six indoor tests of Kilfrost ABC-S neat are compared in figure 30 with respect to failure call. This figure clearly shows the shorter times obtained using the 30% slush failure call. When the 30% white snow failure call is employed, the times are more similar to those obtained outdoors. Although not presented here, the results for the dilutions of Kilfrost ABC-S showed similar results.

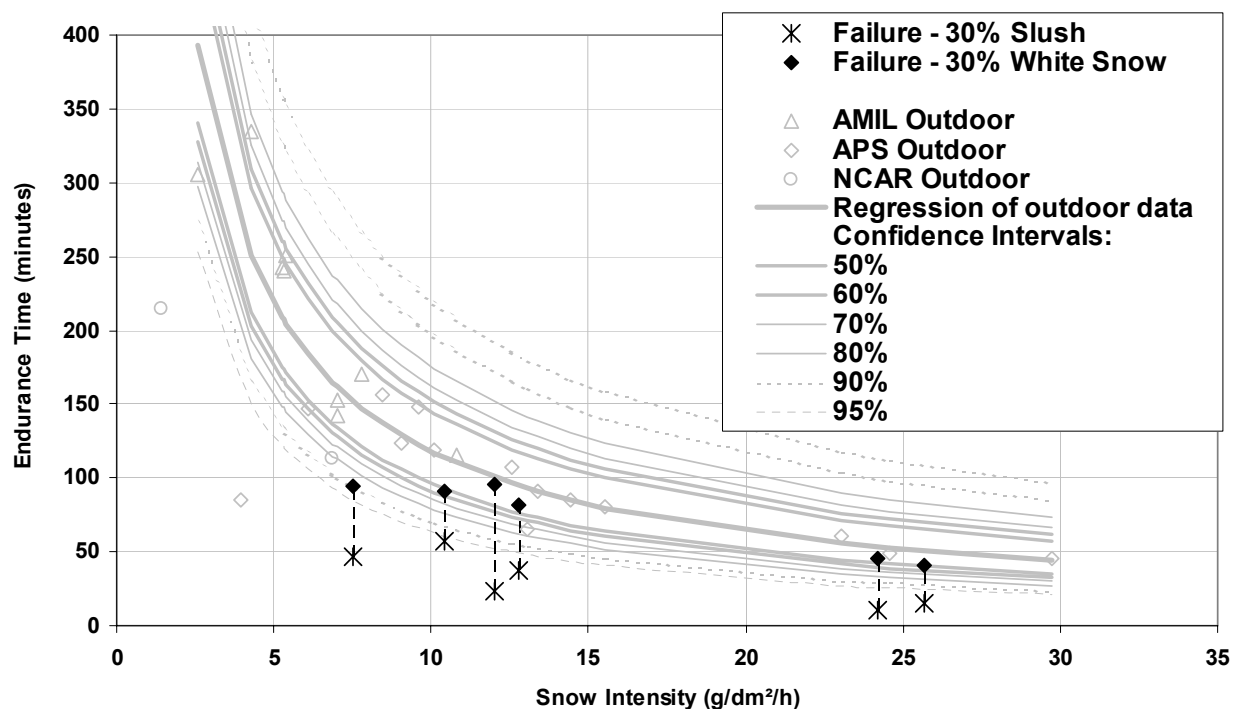


FIGURE 30. KILFROST ABC-S NEAT, COMPARISON OF SLUSH AND WHITE SNOW FAILURE CALL

3.2.3.2 SPCA AD-480 Neat, Differences in Failure Call.

Four indoor tests of SPCA AD-480 neat are compared with respect to the failure call in figure 31. This figure clearly shows the much shorter fluid endurance times obtained using the 30% slush failure call. When the 30% white snow failure call is employed, the times are more similar to those obtained outdoors. With 30% slush, the points are outside the lower 95% confidence interval. Using 30% white snow, the points fall between the regression line and the 60% confidence interval. Both the 75/25 and 50/50 dilution of this fluid, although not shown, had similar results.

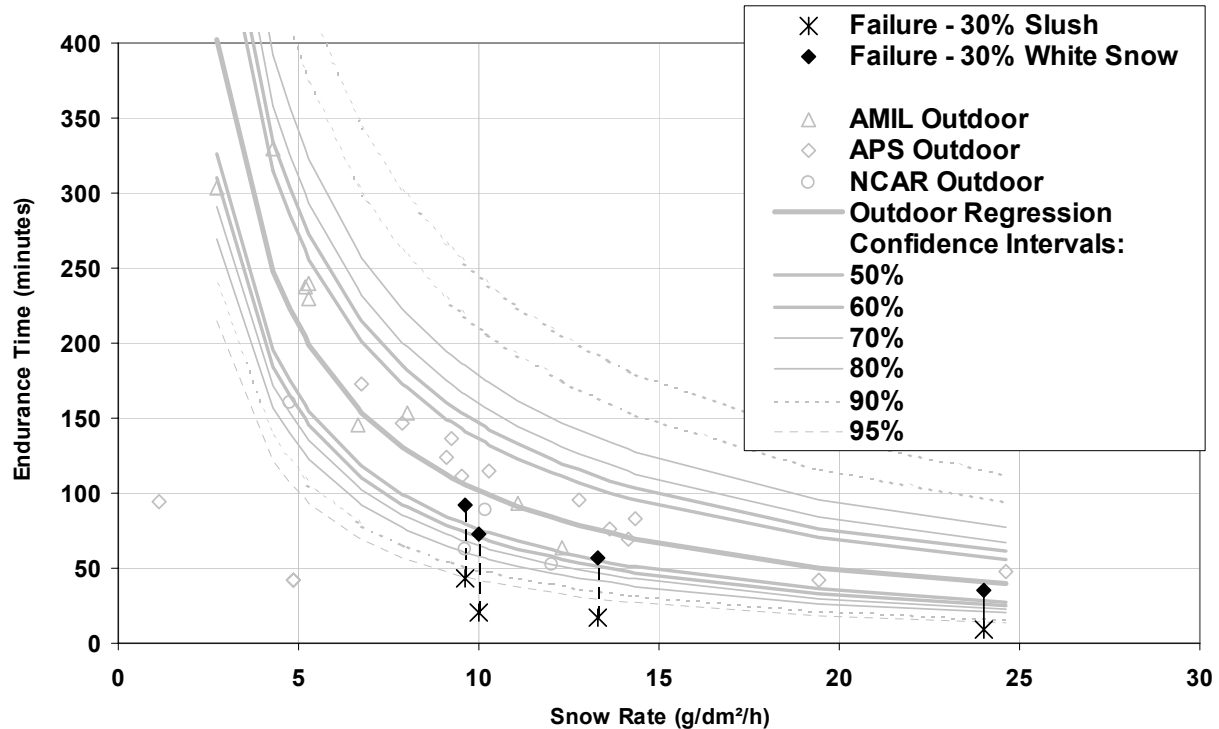


FIGURE 31. SPCA AD-480 NEAT, COMPARISON OF SLUSH AND WHITE SNOW FAILURE CALL

3.2.3.3 Dow Ultra+ Neat, Differences in Failure Call.

Five indoor tests of Dow Ultra+ are compared with respect to failure call in figure 32. As opposed to the other PG-based fluids, the difference between white snow and slush failure calls was less pronounced. Furthermore, since for this fluid, in general, the indoor times were slightly longer, when compared to the outdoor data (see figure 26), the shorter times obtained with the slush bring the values closer to the regression line obtained with the outdoor data.

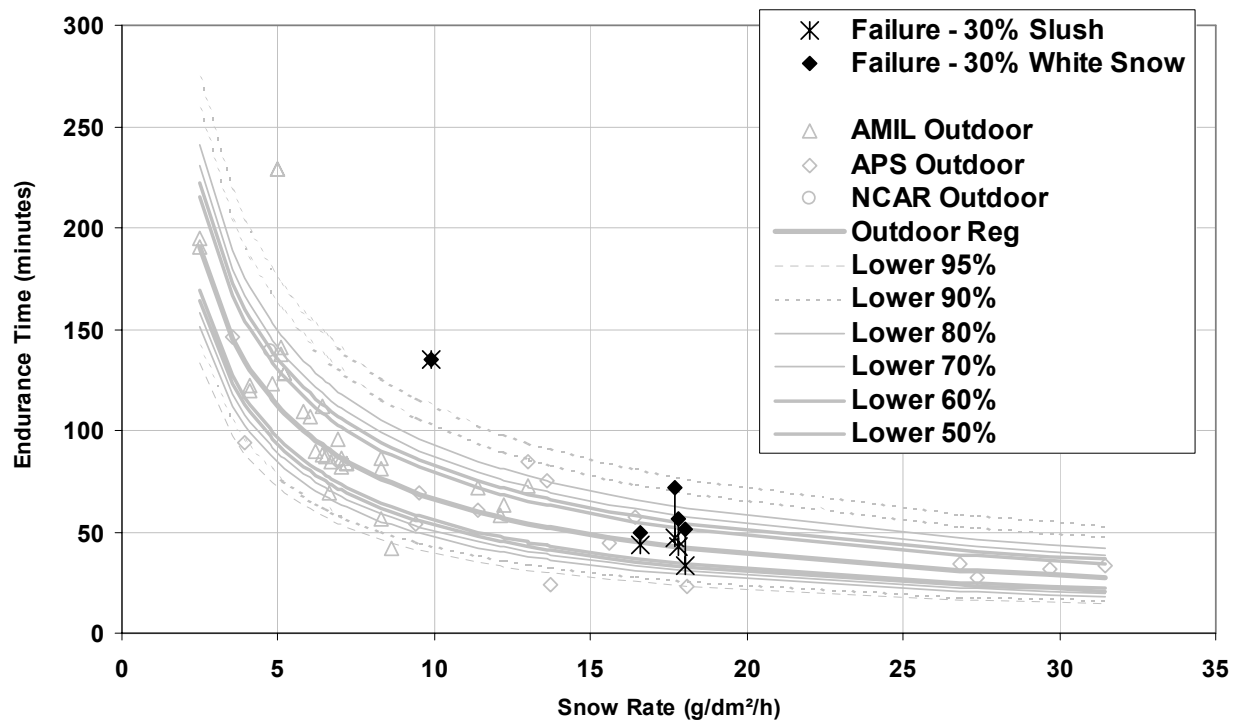


FIGURE 32. DOW ULTRA+ NEAT, COMPARISON OF SLUSH VERSUS WHITE SNOW FAILURE CALL

3.2.3.4 Differences in Failure Call, Conclusion.

The endurance time values for most fluids (obtained with the 30% snow failure call) more closely resembled the values obtained outside. All snow tests conducted inside used the 30% snow criteria to call failure, since the 30% snow was the failure criteria used outside.

3.2.4 The Effect of Wind.

One of the main differences between outdoor and indoor tests is the presence of wind. In the outdoor tests conducted at AMIL, the wind varied from 0.2 to 8.3 m/s. If the wind was any stronger, the tests had to be stopped because the fluids would not pour onto the plates nor would the wind or snow remain in the snow catch pans. Indoors, however, there is little wind. Moreover, no wind is best to ensure an even distribution over the test plate.

The wind effects the tests in three ways: (1) by effecting the temperature of the test, setup by equilibrating by means of convective heat transfer, (2) the wind can effect the shear stress of the fluid and consequently its viscosity, and (3) the wind can effect the quantity of the fluid on the plate by either pushing the fluid up on the plate or pushing it down.

3.2.4.1 The Effect of Wind on Temperature.

In a standard anti-icing endurance test, where the plate is exposed to freezing precipitation, the plate warms up as supercooled water droplets fall on the fluid-coated plates. When this water crystallizes, it releases a latent heat of crystallization as it changes to its more stable form, and this energy is transferred to the fluid and test plate. Snow, however, does the opposite. When the snow falls on the fluid-coated plate, the fluid needs energy to melt the snow crystals, this energy must be taken from the surroundings, including the test plate. Therefore, for snow tests, the plates cool down below ambient air temperature while the fluid is absorbing snow. When the tests are conducted outdoors, the air circulation around the plate is good, and the difference between the plate and air temperature may be at a minimum. However, when tests are run indoors, the plate temperature can be as much as 4 degrees below that of the air. Figure 33 shows an example of one fluid tested outside and then replicated in two different ways inside. The black lines represent data obtained in the outdoor test. The outdoor air temperature, represented by the dashed line, was around -7°C and varied little throughout the test. The plate temperature, represented by the solid line, initially was at -6.5°C , descended to about -8°C , then caught up with the air temperature about 80 minutes into the test; the fluid failed at 116 minutes. When this test was replicated in the lab, represented by the light gray lines, the air temperature was set at -8°C , represented by the dashed line. However, the plate temperature (represented by the solid light gray line), in this case, began around -8°C but quickly descended to -12°C , 4 degrees below the air temperature. When the fluid failed (30% white snow) after 70 minutes, the plate temperature was just starting to heat up, represented by the inflection at the end of the solid light gray line. This represents a time when the fluid is no longer capable of absorbing any more fluid.

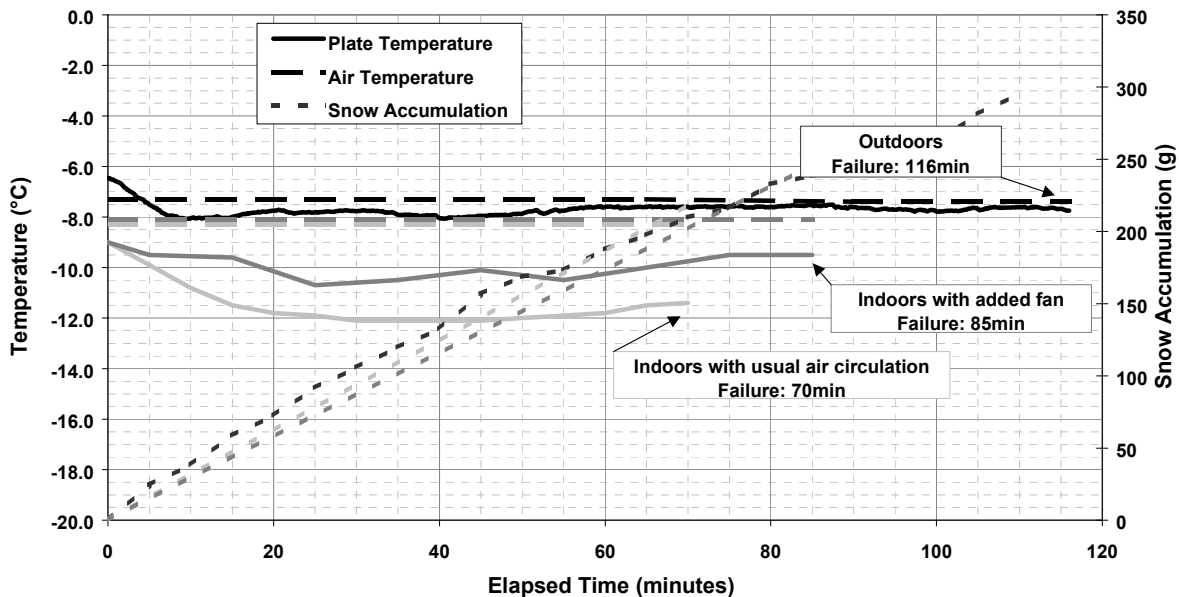


FIGURE 33. EXAMPLE OF THE RELATION OF TEMPERATURE FOR ONE TEST OF KILFROST ABC-S NEAT

In order to help the air circulation and narrow the temperature difference between the air and the test plate, a fan was placed under the test plate to improve circulation but not disturb the distribution of the snow over the plate. The data from this test is represented by the dark gray lines. It shows that, for this situation, there was less of a difference between the air and plate temperatures. The plate temperature only descended to -10.5°C , as represented by the solid dark gray line. This smaller temperature difference led to a longer endurance time of 82 minutes, closer to the value obtained outdoors.

Figure 34 shows a similar example for Kilfrost ABC-S 75/25 dilution. The same outdoor test condition is presented by the black lines, where the fluid failed after 66 minutes. When similar test conditions were carried out indoors, represented by the light gray lines, a 3° temperature drop for the test plate, with respect to the air temperature, was recorded (represented by the solid light gray lines and long dashed lines, respectively). The fluid lasted 58 minutes before being covered with 30% white snow. This result is very similar to the result obtained outside. When a fan was added under the test plate, the difference between the air and plate temperature was reduced to 2° , as represented by the dark gray lines. However, the endurance time of the fluid remained essentially the same at 59 minutes.

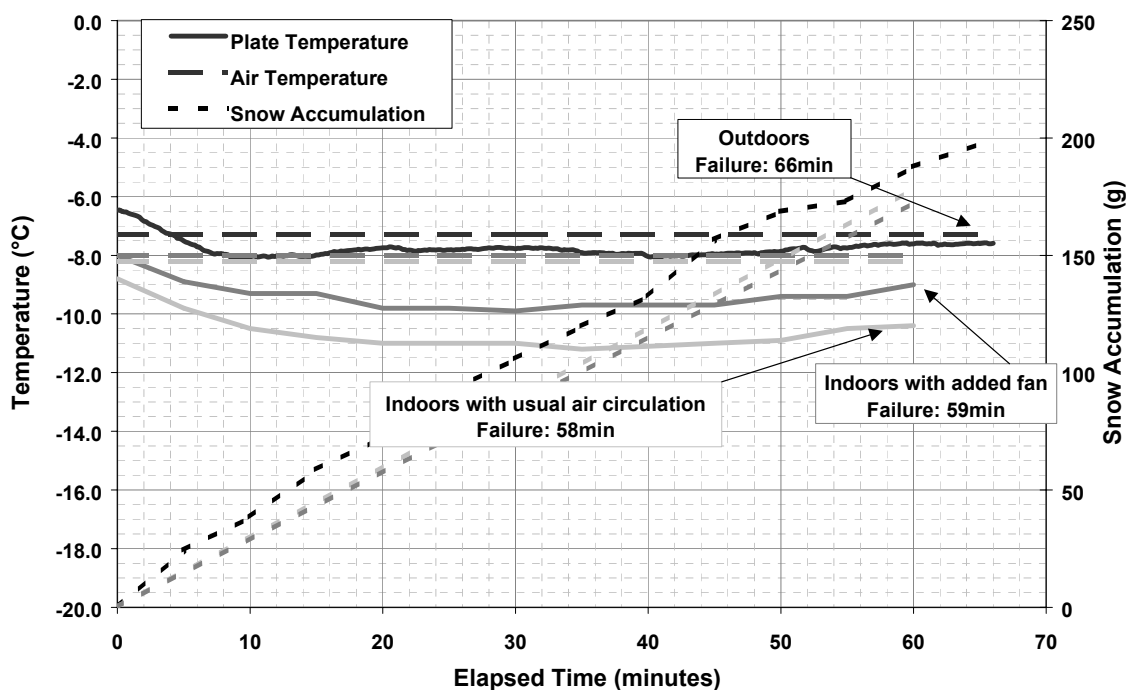


FIGURE 34. EXAMPLE OF THE RELATION OF TEMPERATURE FOR ONE TEST OF KILFROST ABC-S 75/25 DILUTION

Figure 35 shows a similar example for SPCA AD-480 neat. For the same outdoor test, represented by the black lines, the fluid failed after 93 minutes. When similar test conditions were carried out indoors, represented by the light gray lines, a failure time of 58 minutes was obtained, and there was a 4° temperature difference between the plate and air temperatures. When the test was repeated with a fan under the plate, to encourage air circulation (represented

by the dark gray lines), the fluid lasted longer, with an endurance time of 70 minutes and a 2° temperature difference between the air and the plate. In both indoor tests, the plate temperature quickly decreases once the fluid begins to absorb the falling snow, bottom out at a temperature below that of air, and stay constant. Then at failure, the plate begins to warm up, as seen by the inflection of the solid lines, because the fluids are no longer absorbing snow.

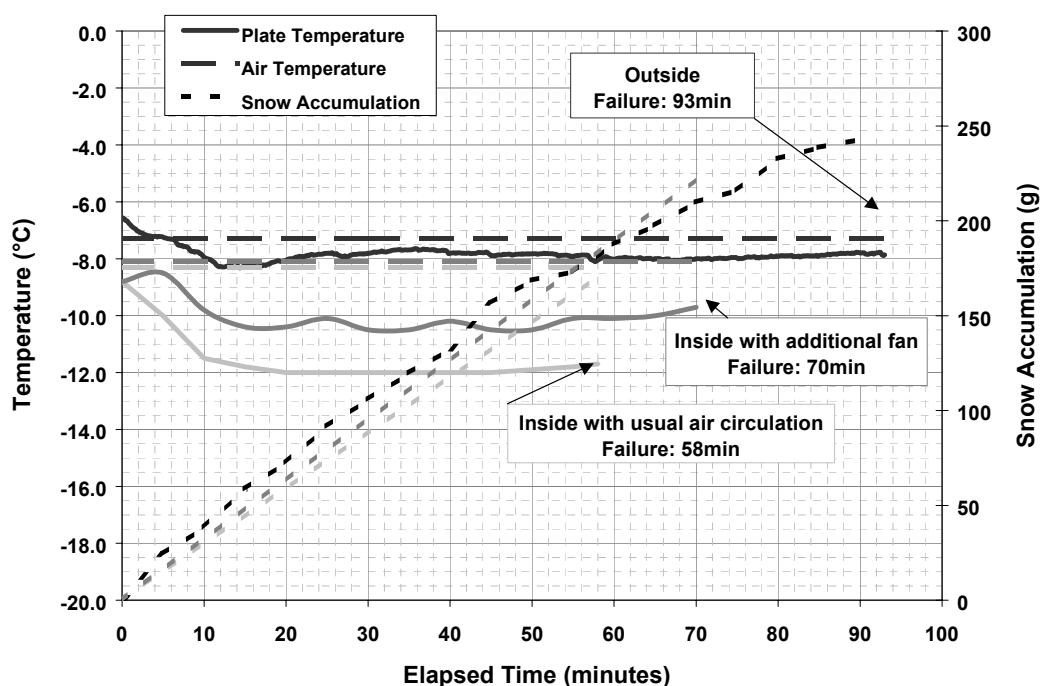


FIGURE 35. EXAMPLE OF THE RELATION OF TEMPERATURE FOR ONE TEST OF SPCA AD-480 NEAT

Figure 36 shows a similar example for SPCA AD-480 75/25 dilution. The same outdoor test condition, as for the other fluids, is represented by the black lines. This fluid failed after 64 minutes. When the test conditions were replicated indoors, there was a 3.5° temperature difference between the air and plate temperatures, as represented by the dashed and solid light gray lines, respectively. In this case, the fluid failed after 47 minutes. When a fan was added under the test plate, the difference between the air and plate temperatures was reduced to 2° , as represented by the dashed and solid dark gray lines. In this case, the endurance time of the fluid was only increased to 50 minutes.

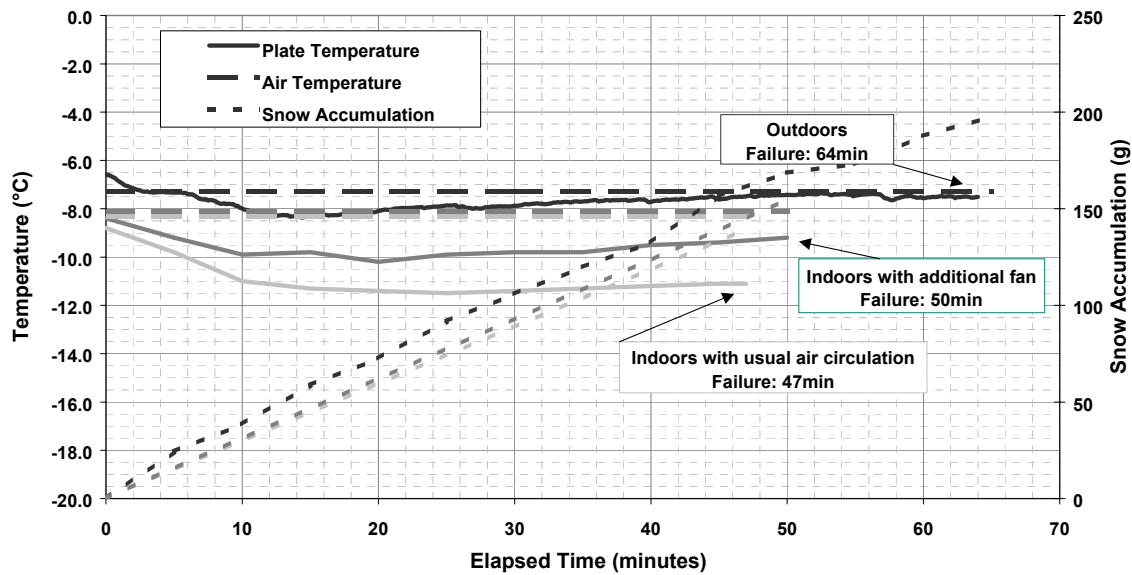


FIGURE 36. EXAMPLE OF THE RELATION OF TEMPERATURE FOR ONE TEST OF SPCA AD-480 75/25 DILUTION

However, the relation between the differences in air and plate temperatures are not the same for all fluids. Figure 37 shows results for Dow Ultra+ under the same tests conditions. In this example, the outdoor fluid endurance time was 63 minutes, as represented by the black lines, with an air and plate temperature difference of about 1° . When this test was replicated indoors with the usual air circulation, a time of 85 minutes was obtained, with a temperature difference between the air and the plate of about 5° , as represented by the light gray lines. Despite the large temperature difference, the fluid lasted longer indoors. When wind was added under the test plate, the fluid lasted 75 minutes, and the temperature difference between the air and the plate was reduced to a maximum of 3° .

Therefore, despite a longer time with a larger temperature difference, by narrowing the air and plate temperature difference, the fluid's endurance time more closely resembled that value obtained outside.

3.2.4.2 The Effect of Wind on the Fluid Viscosity.

All fluids tested were Type IV fluids (non-Newtonian) and, therefore, effected by shear stress. The wind action on the fluid will, to some extent, shear the fluid.

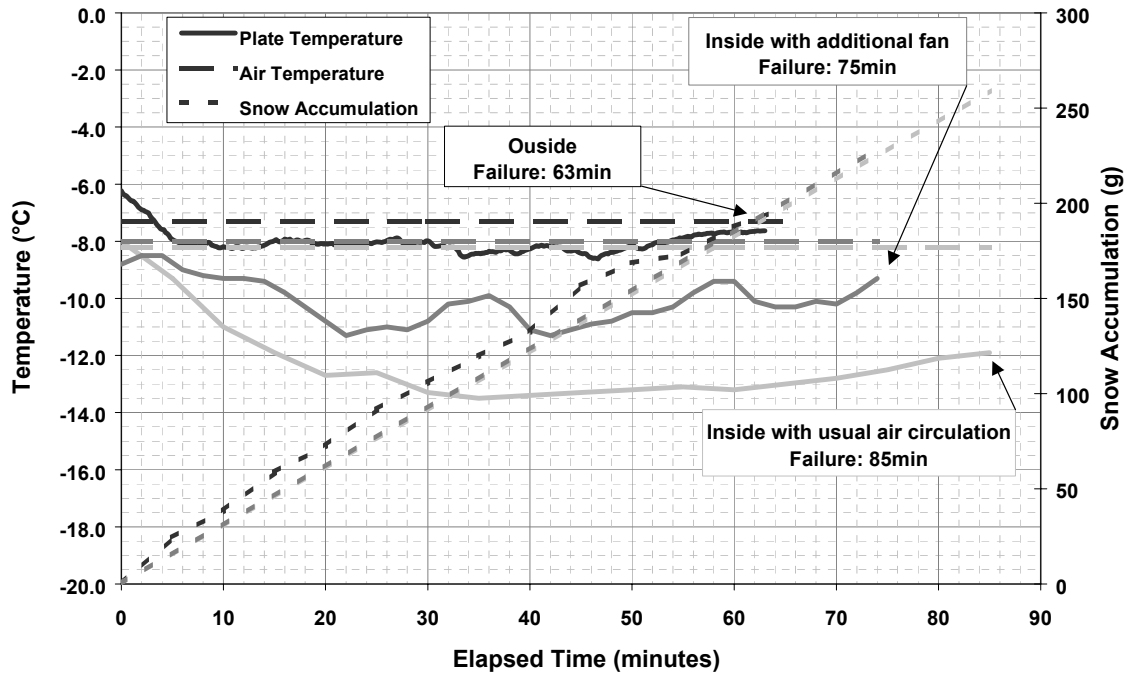


FIGURE 37. EXAMPLE OF THE RELATION OF TEMPERATURE FOR ONE TEST OF DOW ULTRA+ NEAT

The shear forces acting on the fluid on the plate are gravity and wind. The gravitational shear stress acting on the fluid on the plate is in the order of 3.7 Pa. The average wind speed recorded in outdoor tests, at AMIL, was in the order of 4 m/s (see figure 38). This equals a shear force of 0.04 Pa in the center of the test plate according to:

The wall shear stress

Laminar
$$\tau_w = 0.332 \cdot \mu_a \cdot \frac{U}{x} \cdot \sqrt{\text{Re}_x} \quad (2)$$

Turbulent
$$\tau_w = 0.0225 \cdot \rho_a \cdot U^2 \cdot \left(\frac{\mu_a}{\rho_a} \cdot \frac{\text{Re}^{0.2}}{0.368 \cdot U \cdot x} \right)^{0.25} \quad (3)$$

where:

- τ_w = Wind shear stress
- Re = Reynold's number
- μ = dynamic viscosity
- ρ = density
- U = wind speed
- X = position on the test plate

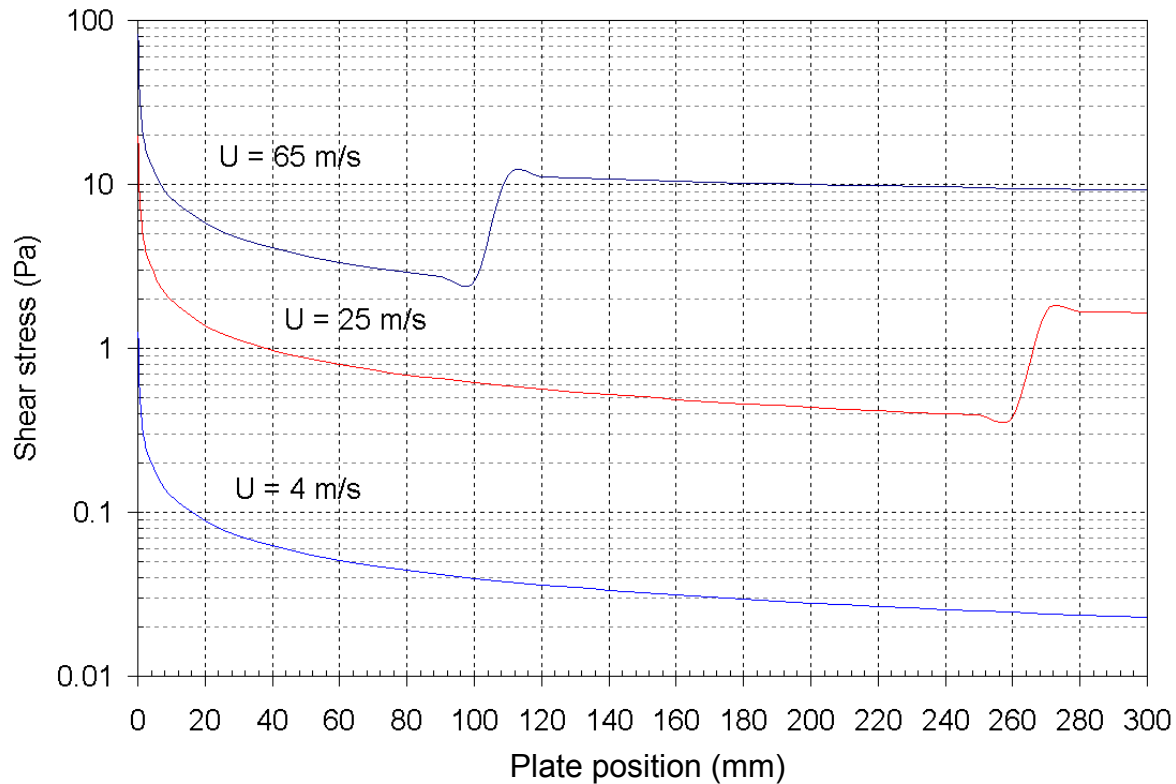


FIGURE 38. SHEAR STRESS DISTRIBUTION ALONG THE TEST PLATE

A wind speed of at least 25 m/s (50 knots), where some turbulent flow would be present, would be required to significantly affect the viscosity of the fluid on the plate. Therefore, the wind's effect on the fluid viscosity was not considered a persuasive factor.

3.2.4.3 The Effect of Wind on Fluid Thickness.

For the tests conducted outdoors, the test plates were setup facing the wind. If the wind is blowing up the plate, the thickness of the fluid could be increased because it is held back from flowing off the plate, or the thickness could decrease as it is being pushed over the top or sides of the plate. This effect could be different for different fluids at different wind speeds. A quick study was undertaken to examine the effect of wind blowing up the plate on fluid thickness. For this study, each fluid (neat) was poured onto the test plate indoors with a fan facing the plate set at different speeds, as well as off, and the weight of the test plate was recorded for 1 hour.

Figure 39 summarizes the results, showing the fluid thickness, in grams, 30 minutes after the start of the test for four different wind speeds, as well as no wind. For Kilfrost ABC-S, a wind speed of 1.8 m/s resulted in a thicker fluid after 30 minutes than with no wind. However, with Dow Ultra+, there is a steady drop in fluid thickness with increasing wind speed. For SPCA AD-480, there is a slight decrease in fluid thickness with 1.8 m/s wind, then it steadies to 6.9 m/s, after which it decreases abruptly as virtually all the fluid has flowed off the plate at 8.3 m/s.

Figure 39 can explain some of the differences between indoor and outdoor data. The Kilfrost fluid had slightly longer times outside; this may be partially explained by the added wind, which held the fluid on the plate. The Dow Ultra+ fluid, which has slightly shorter times outside, may also be explained by the fact that there was less fluid on the plate due to the wind. However, SPCA AD-480 had the same or slightly longer times outside, but according to figure 39, one would expect the same or slightly shorter times outside since the wind pushed some of the fluid off the plate. Therefore, the effect of wind on fluid thickness is probably one factor of many affecting the differences between indoor and outdoor tests.

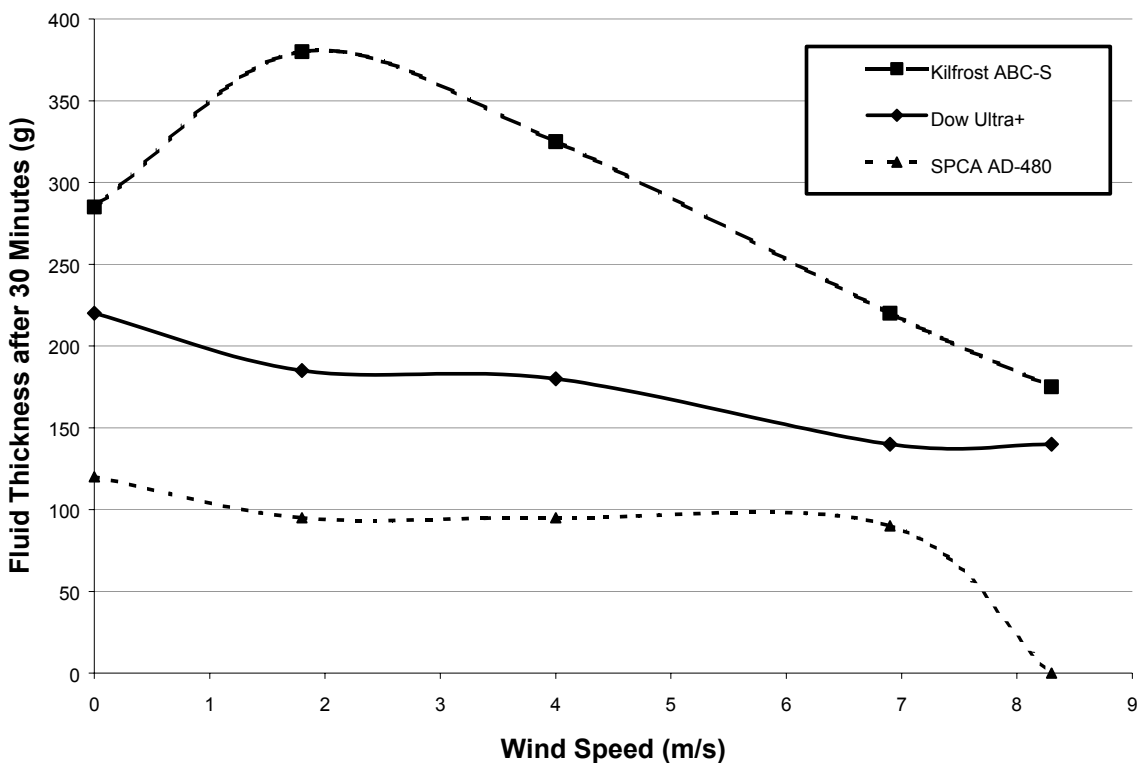


FIGURE 39. EFFECT OF WIND SPEED ON FLUID THICKNESS

This effect was then tested on fluid endurance time tests. For each fluid (neat) a few tests were run with the fan placed in front of the plates, generating a wind speed of 1.8 m/s. Figure 40 shows the same test presented previously with the addition of data from the test with wind blowing up the plate, represented by the bold lines. The results show a longer endurance time of 96 minutes, closer to the value obtained outdoors of 116 min. It also shows a smaller difference between the air and plate temperatures. For this test, the difference was only about 1°, similar to values obtained outdoors. This longer result with wind is most likely due to the fact that more fluid is on the plate, as shown in figure 40, as well as the fact that the plate temperature is the same as the air.

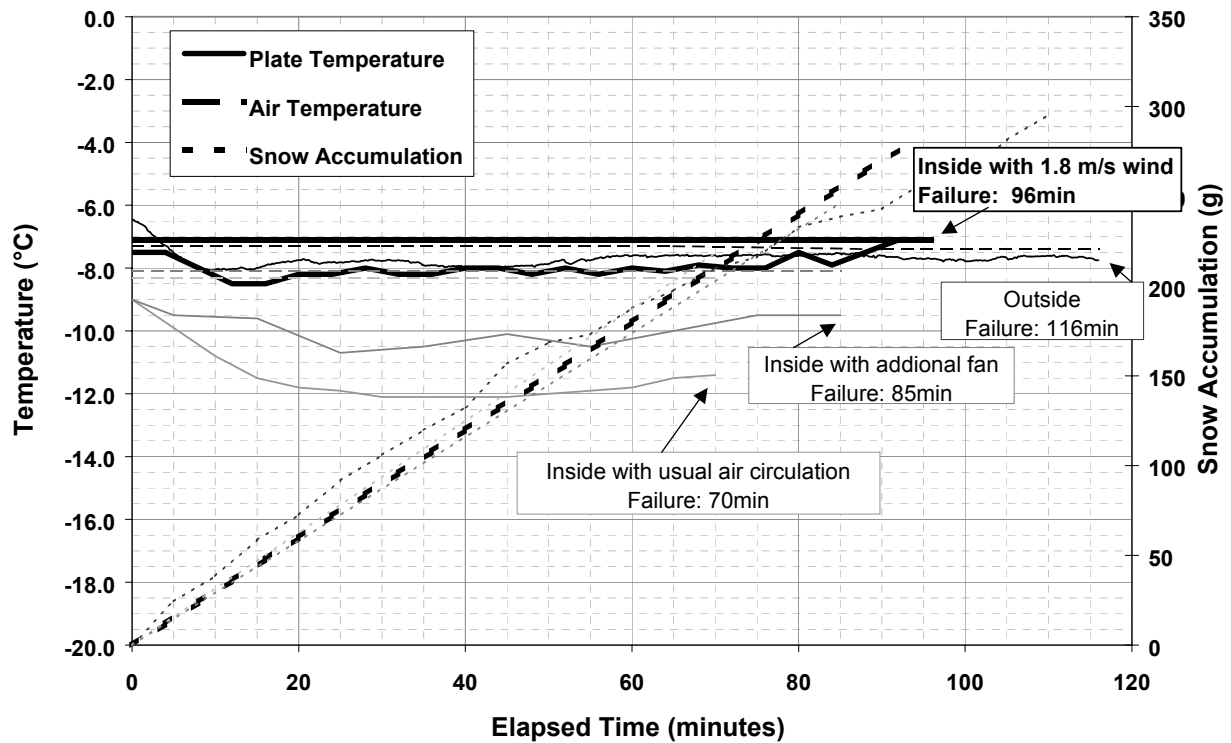


FIGURE 40. INDOOR TEST OF KILFROST ABC-S NEAT WITH FAN AT 1.8 m/s BLOWING UP THE PLATE

Figure 41 shows the results of a similar test performed on SPCA AD-480 with wind blowing up the plate at 1.8 m/s, represented by the bold lines. The data from similar tests with the same fluid are equally presented. The graph shows that, with wind, the failure is reduced to 57 minutes, shorter than the 93 minutes observed outside. It also shows a greater difference in temperature between the air and the plate, 2°, more than seen with Kilfrost ABC-S. This shorter time may, in part, be the result of the fluid flowing off the plate, as shown in figure 39.

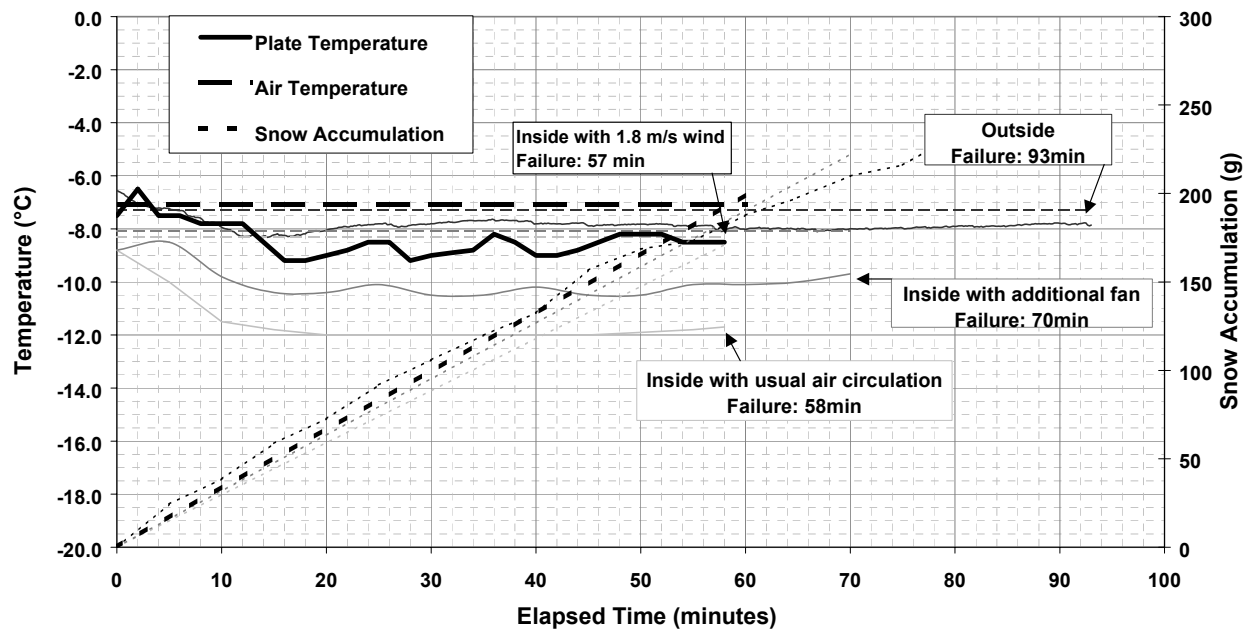


FIGURE 41. INDOOR TEST OF SPCA AD-480 WITH FAN AT 1.8 m/s BLOWING UP THE PLATE

Figure 42 shows the same example for Dow Ultra+. The figure shows that the wind blowing up the plate, represented by the bold lines, results in an even longer endurance time (135 minutes) than all the other cases. This is more than twice the value obtained outdoors. Note that for this test the intensity was around 10 g/sm²/h, as opposed to the 12 g/sm²/h in the other cases, but either way, the endurance time is still much too long. This goes against the theory presented in figure 39, where the fluid thickness could influence the endurance time. For Dow Ultra+, with a wind speed of 1.8 m/s, the fluid thickness decreased and, therefore, the endurance time should have decreased as well.

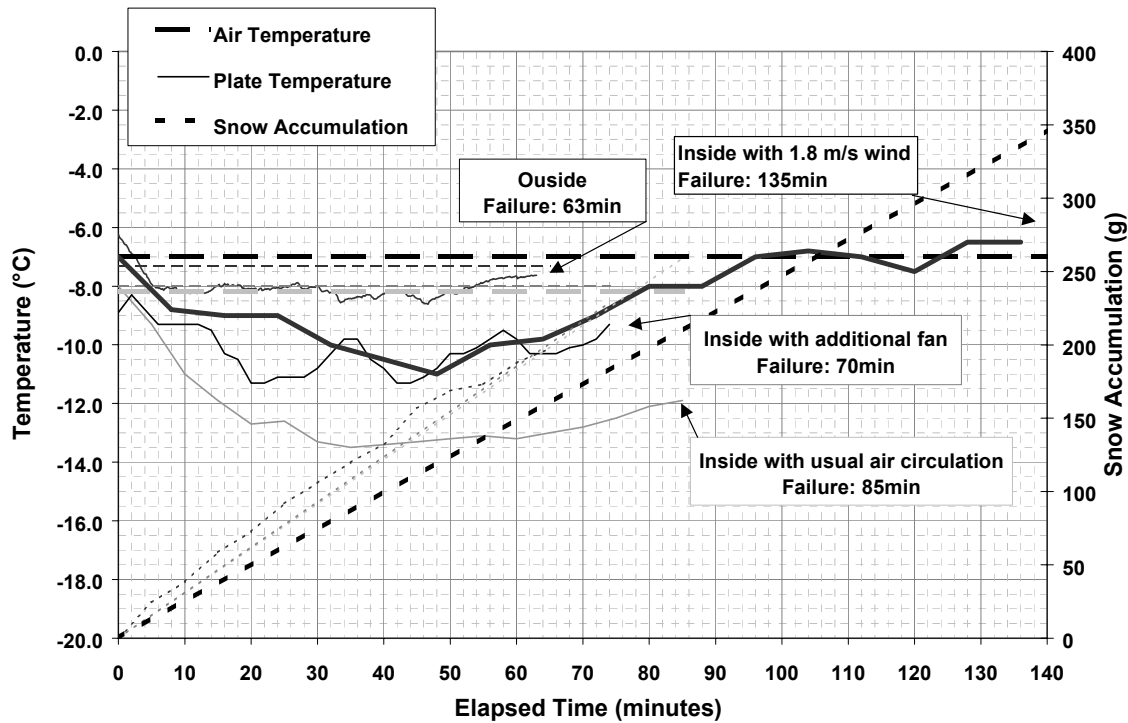


FIGURE 42. INDOOR TEST OF DOW ULTRA+ WITH FAN AT 1.8 m/s BLOWING UP THE PLATE

3.2.5 Controlling the Plate Temperature.

Based on the indoor test results presented in the preceding sections, the most promising factor to obtaining the same values inside as outside was the plate temperature. The plate temperature was the same as, or less than, 1° below the air temperature outside; therefore, the same should be tried for the indoor tests.

Preliminary tests were run under the same conditions at AMIL. Each fluid (neat) was tested only one time. The same plate temperature was achieved using a system of recirculating heat transfer fluid coupled to a heat exchange cell under the test plate. The system used was similar to the frosticator system in the Water Spray Endurance Test setup (Annex A of AMS1424 [4]).

Figure 43 shows a comparison of anti-icing endurance tests for ABC-S neat. The graph shows that although all indoor tests fall in the range of the regression line and the lower 95% confidence interval of the outdoor data, it is the times obtained with the wind over the test plate that are closest to the regression line. The data point obtained using the frosticator chiller unit were in the same range as the points obtained with the wind under the test plate.

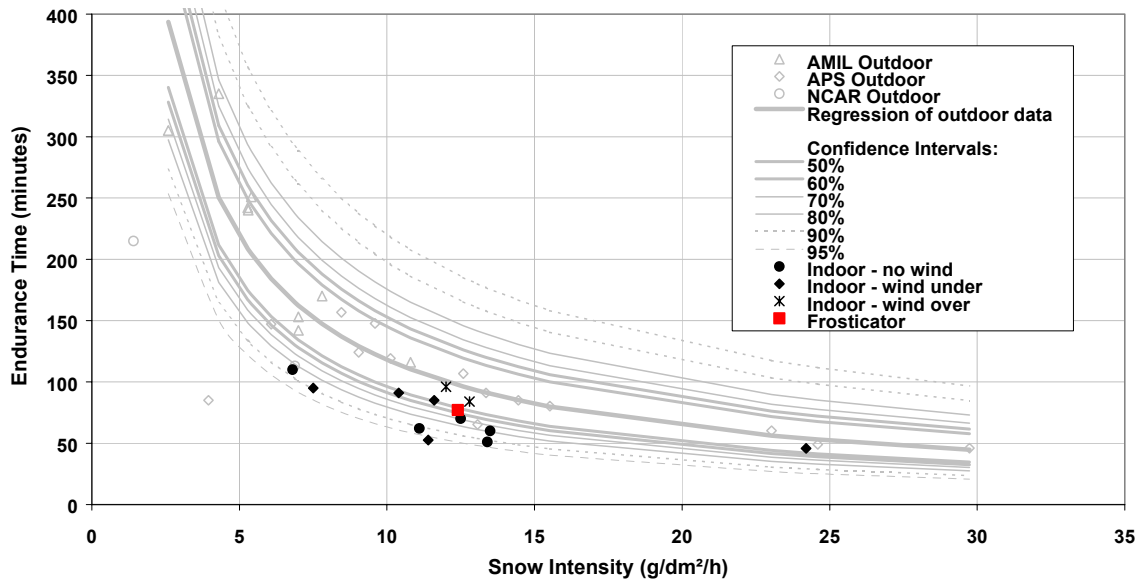


FIGURE 43. COMPARISON OF KILFROST ABC-S NEAT ANTI-ICING ENDURANCE TIMES

Figure 44 shows a comparison of anti-icing endurance times for SPCA AD-480 neat. The graph shows that with the frosticator, the value was in the range of the lower 50% confidence interval, as with the Kilfrost ABC-S fluid, in the same range as the points with the wind under the test plate.

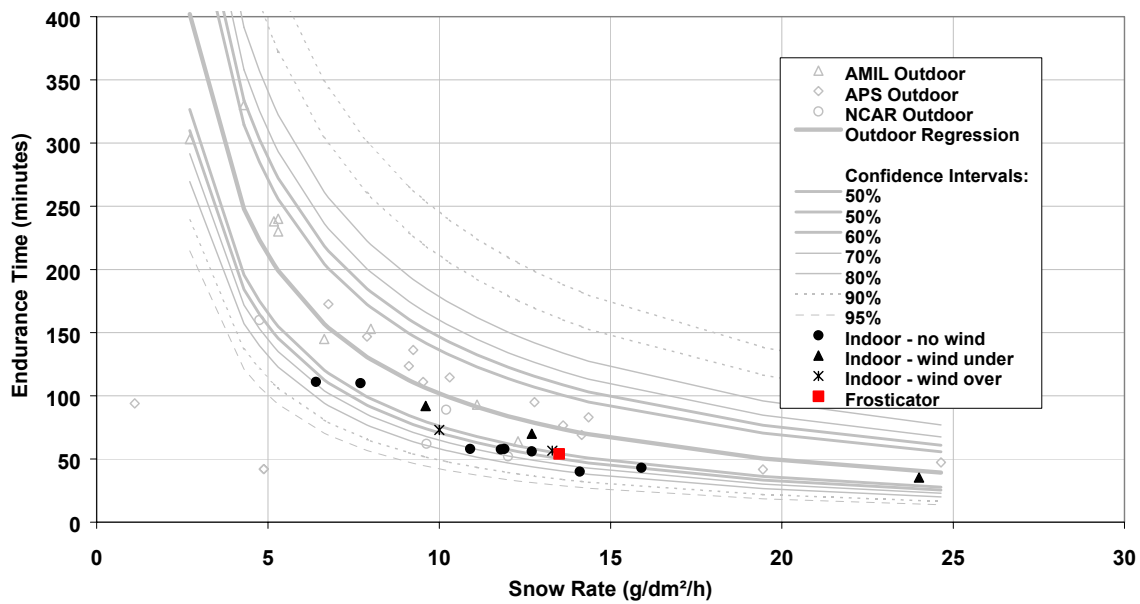


FIGURE 44. COMPARISON OF SPCA AD-480 NEAT ANTI-ICING ENDURANCE TIMES

Figure 45 shows a comparison of anti-icing endurance times with Dow Ultra+ neat. This graph shows that, in general, all the data obtained indoors falls between the regression line and the upper 95% confidence interval and beyond, as opposed to the other fluids, where the indoor data was below the regression line. For this fluid, the tests with the frosticator showed the most promise, with one test falling on the regression line, below all points previously obtained.

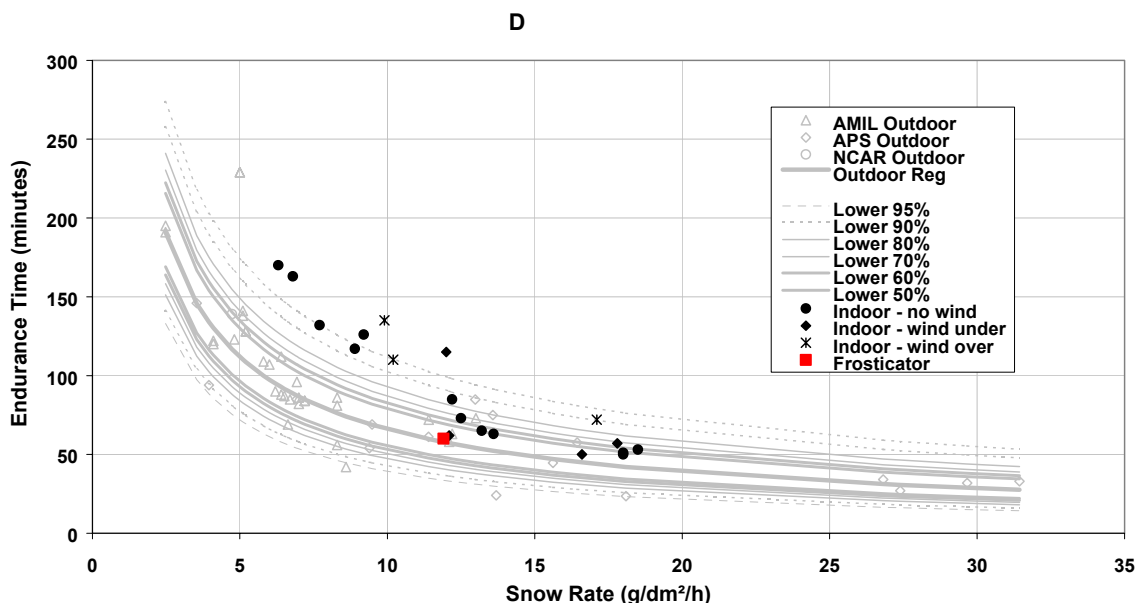


FIGURE 45. COMPARISON OF DOW ULTRA+ NEAT ANTI-ICING ENDURANCE TIMES

4. DISCUSSION.

In order to reproduce outdoor values inside, replicating air temperature and intensity using artificially generated snow proved adequate to obtaining results obtained outside, within the upper and lower 95% confidence intervals for all fluids tested. However, for two of the fluid, Kilfrost ABC-S and SPCA AD-480, these indoor values tended to fall between the regression line and the lower 95% confidence interval. For Dow Ultra+, these values fell between the regression line and the upper 95% confidence interval. Therefore, other factors that are different between inside and outside tests had to be examined. Factors, such as artificial versus natural snow and failure call, were examined in the results section and proved to have little or no influence on the fluid endurance time. The one factor that proved to effect the endurance times was the wind, especially its influence on the plate and, therefore, fluid temperature.

Many trials were run to see the effect of the wind on the endurance time, their results are summarized in figure 46. This graph shows the relation of the data obtained inside with respect to the regression line and the confidence intervals determined from the outdoor data. The x's represent indoor tests and are placed in relation to the confidence intervals. Horizontal lines were drawn to group the indoor tests for a given condition to see the range of data from one confidence interval to another. For example, for ABC-S neat, the indoor data with no wind ranged from the lower 95% confidence interval to the lower 70% confidence interval. For the

case with wind added under the test plate, the indoor data ranged from beyond the lower 95% confidence interval to the upper 50% confidence interval and so on.

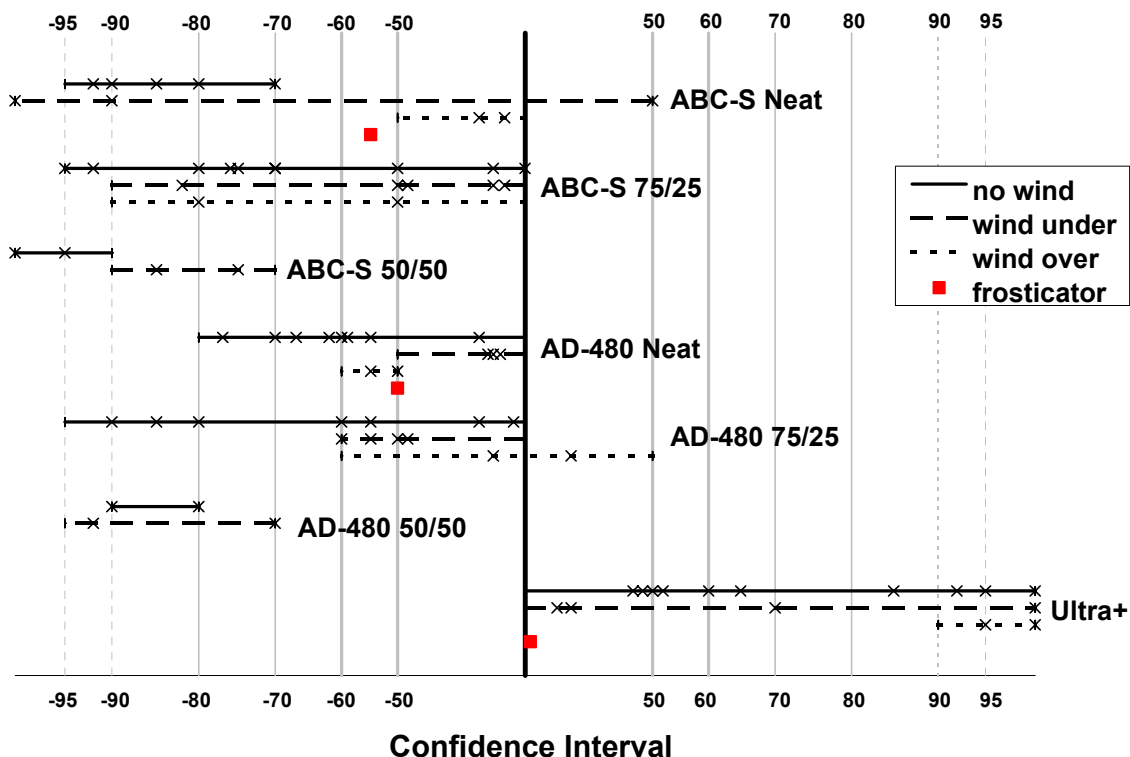


FIGURE 46. A COMPARISON OF ENDURANCE TIMES OBTAINED INDOORS WITH RESPECT TO THE CONFIDENCE INTERVALS

The graph shows that, in general, the wind under the test plate provided results that are most clustered around the regression line, with the exception of ABC-S neat and AD-480 75/25, where the data obtained with the wind over the test plate is most clustered around the regression line. This may have to do with the fact that the wind is pushing the fluid up the plate, as seen in figure 39. For all fluids, the case of the frosticator chilling unit showed promise as it fell within the lower 60% confidence interval and the upper 50% confidence interval. Clearly, more tests need to be conducted to prove its usefulness. However, for a standardized test method, this may be most useful since the test conditions can easily be defined, reproduced and repeated, with no difference in wind speeds, heat transfer, etc., brought about by a subjective system such as wind.

5. CONCLUSIONS.

Outdoor and indoor snow tests conducted on three Type IV fluids and their dilutions showed that using the artificially generated snow and the AMIL snow distribution machine, the indoor results fell within the upper and lower 95% confidence intervals generated from outdoor testing for all fluids tested. However, for two of the fluids, Kilfrost ABC-S and SPCA AD-480, these indoor values tended to fall between the regression line and the lower 95% confidence interval. For Dow Ultra+, these values fell between the regression line and the upper 95% confidence interval.

Further investigations into four factors showed that:

1. Whether artificial or natural snow is inserted in the snow box, there is no difference in the endurance times of the fluids. Therefore, the artificially generated snow can be considered as equivalent to the natural snow.
2. When different snow cluster sizes were used on the AMIL snow distribution machine, no significant differences were observed in fluid endurance time. However, tests with the smaller clusters had failures which appeared more realistic, further resembling the outdoors tests. Therefore, the smaller cluster size was adopted in the laboratory because of the better distribution obtained.
3. When the failure call of 30% white snow was used, as opposed to a failure call of 30% slush, values obtained indoors more closely resembled those obtained outdoors.
4. Wind has a large effect on endurance time of the fluids, with respect to the fluid temperature and the fluid thickness, but not on the fluid viscosity. When tests were run outdoors, there was little or no difference between the plate and air temperatures, however, inside there could be great difference. By regulating this temperature difference better times could be obtained inside.

6. RECOMMENDATIONS.

1. More indoor data on the effect of wind on the endurance times of the fluids is needed, especially with the test plate temperature controlled.
2. Consider performing similar tests on Type I and Type II fluids.

If the future test results concur with the conclusions of this report, a standard indoor test procedure for measuring anti-icing endurance time on fluids could be adopted, based on a test method consisting of artificially generated snow from a snow distribution machine, dispensed onto test plates whose temperature is independently controlled to be the same as the air temperature.

7. REFERENCES.

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